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**Article**

# Numerical Analysis and Staircase Layout Optimisation for a Ro-Ro Passenger Ship during Emergency Evacuation

**Xinjian Wang [a, b], Zhengjiang Liu [a, b], Sean Loughney [c], Zaili Yang [c, d], Yanfu Wang [c, e], Jin Wang [c *]**

[a] Navigation College, Dalian Maritime University, Dalian 116026, P.R. China
[b] Key Laboratory of Navigation Safety Guarantee of Liaoning Province, Dalian 116026, P.R. China
[c] Liverpool Logistics, Offshore and Marine (LOOM) Research Institute, Liverpool John Moores University, L3 3AF, UK
[d] Transport Engineering College, Dalian Maritime University, Dalian 116026, P.R. China
[e] College of Mechanical and Electronic Engineering, China University of Petroleum, Qingdao 266580, P.R. China

## Abstract

In this research, the effects of the passenger population composition and ship familiarity in an emergency evacuation are analysed. The results identified that the effects of different population compositions on the Ro-Ro evacuation process vary significantly. It is therefore recommended that a targeted survey of the population on a specific ship should be conducted before the evacuation analysis to improve the analysis accuracy of the evacuation process. It is not always the case that a higher familiarity with the ship staircase layout necessarily results in less time to complete the evacuation, and the issue of balanced exits has to be considered due to its significant impact. The results obtained in this research can be used to aid the ship's staircase layout optimisation to facilitate the evacuation process. Given the type of Ro-Ro vessel in this analysis, it is suggested that adding a staircase towards the bow of the ship can reduce the evacuation time by 13.6%, when considering 95% of the passengers to complete an evacuation. Similarly, adding one staircase at the stern can reduce the time by approximately 10% for all passengers to complete the evacuation. It is not recommended that the size of staircases towards the middle of the ship should be adjusted.

* Corresponding author: j.wang@ljmu.ac.uk (J. Wang)

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## 1. Introduction

In recent years, the frequency and scale of crowd events have been increasing, and the issue of the safe evacuation of individuals in crowded spaces has attracted increased attention [1-3]. This has stimulated the research in the fields of emergency preparedness and evacuation modelling [4, 5]. In order to improve the efficiency of an emergency evacuation process, significant research works have been carried out on land buildings [1, 6], nuclear power systems [7, 8] and aircrafts [9, 10], land public transport systems [11, 12], offshore platforms [13, 14], passenger ships [15-18] and other fields. Studies on emergency evacuations stimulate the development of predictive models and simulation tools to assess the effectiveness of evacuation planning, architectural design, and crowd management strategies, and improve the level of safety management [2, 4, 17, 19].

Maritime transport plays an important role in the integrated transport system, especially in the international trade system [5, 20]. It interacts with a variety of modes of transport and industries [21, 22]. Passenger ships are an important part of the maritime transportation industry [16, 21, 23]. Although modern ships have made continuous progress in their structural design, operating practices, marine technologies and regulations [16, 24, 25], passenger ship accidents such as the "Costa Concordia" that capsized in 2012 and the "Sewol" that sank in 2014 still occurred with catastrophic consequences [26-28]. It is generally believed that the complexity of modern ship design and operation makes accidents inevitable, and that to some extent improving emergency response should take precedence over (so to speak) emergency prevention [19, 29]. As a favourable measure to reduce the impact of accidents, evacuation planning is an important part of emergency response [4, 30]. It is vitally important in the maritime industry due to the remoteness, the need to be fully self-sufficient and bad weather conditions [5, 30].

Ro-Ro passenger vessels are safety sensitive, as an accident can cause serious fatal consequences [24, 31, 32]. In the event of a serious passenger vessel accident, evacuation is considered to be the last resort to reduce human losses [33, 34]. Since the 1990s, the International Maritime Organization (IMO) has successively revised the SOLAS Convention to improve the safety of Ro-Ro passenger vessels, especially after the "Estonia" sank in 1994. Furthermore, the IMO Maritime Safety Committee (MSC) has considered the effectiveness of the evacuation route, which must be evaluated at the design stage of Ro-Ro passenger vessels [35-37]. In 2016, after several revisions and updates, the MSC approved the "Revised guidelines on evacuation analyses of the new and existing passenger vessels" (IMO guidelines), which made evacuation analysis mandatory in the design and construction stages not only for Ro-Ro passenger ships but also for other types of passenger ships built after 1st January 2020 [28, 38]. This initiative aims to analyse the inappropriate parts of a ship's layout and congestion points, optimize the evacuation layout to improve personnel safety, and bring a new regulatory concept to the design, construction and operation of passenger ships, which will better meet the future development of the passenger ship industry [35].

The safety issue of passenger vessels has been widely recognised and documented, especially the Ro-Ro passenger vessels and ferries [2, 16, 24, 32]. According to Lloyds Register accident statistics, 5,240 people were killed or injured in fatal passenger vessel accidents worldwide from 2000 to 2020, of which more than 85% were on Ro-Ro passenger vessels or ferries. Due to incomplete reporting, it is estimated that the actual number of deaths is likely to be at least 50% higher than this value, with 80% in 10 developing countries [39]. In view of the high risk stake of passenger vessels, the IMO believes that it is necessary to focus on ferries and Ro-Ro passenger vessels that are not subject to the SOLAS Convention, and strive to improve the safety level of "non-convention" ships such as inland ferries or Ro-Ro passenger vessels on domestic routes [35, 40].

China has a coastline of 18,000 km, numerous islands, and a huge coastal maritime transportation system. Although China's maritime traffic safety has been improved in recent years, severe maritime accidents still occurred. Examples of such accidents include the "Dashun" that sank on the route from Yantai to Dalian in 1999, and the "Eastern Star" that capsized in the Yangtze River in 2015. These two are among the most serious maritime accidents in China [28, 41]. The "Dashun" sinking indicates that the study of the safety of Ro-Ro passenger vessels on the high traffic route from Yantai to Dalian in China is vital. Extensive literature reviews have identified that there are very few studies investigating the safe evacuation of passenger vessels in China, and fewer on the safe evacuation of Ro-Ro passenger vessels on the route from Yantai to Dalian, which does not well reflect the safety demand in practice. Therefore, to bridge this gap, this paper aims at investigating the demographics of passengers and their familiarity with ships on this high traffic route, and using the FDS+EVAC software package [42] to establish a passenger ship evacuation simulation model. This study also explores the influence of the passenger population composition and exit familiarity on passenger vessel evacuation, and identifies the congestion points in the existing ship geometry. The research provides suggestions and recommendations for the optimisation of the ships' staircases layout, evacuation strategies and crowd management, thereby improving the overall safety level of passenger ships.

## 2. Literature Review

Human evacuation can be defined as a systematic mustering, directing, or removal of many people from an area of present or potential danger to a place of relative safety [17, 28]. Considering the growing demand of passenger vessel evacuation assessment in the shipbuilding industry, the IMO considers a long-term comprehensive review of the existing safety evacuation system to ensure that it can meet the challenges of the maritime industry’s needs and social expectations [38, 43]. However, compared with the relatively mature land-based evacuation, the research on ship evacuation only started lately. It is because of two main reasons: firstly, ship evacuation research requires researchers to have specific knowledge of ship structures, navigation environments and related rules; and secondly, due to the complex ship structure and the changeable marine environment, it is not easy to obtain ship evacuation data and the validity of the existing data is generally poor [28, 44].

### 2.1 The uniqueness of passenger vessel evacuation

Generally, emergency evacuation has two main components: the pre-evacuation phase (the time between the evacuation alarm and starting to move to the exit) and the movement phase (the time from the beginning of the move to the exit and arrival at the exit) [17, 28, 45, 46]. However, passenger ship evacuation is complicated, which is affected by many factors [44, 47], as shown in Fig. 1. In addition, the ship's structural environment, personnel evacuation methods and operation procedures are still very different from those of land-based evacuation methods [17, 36, 48, 49].

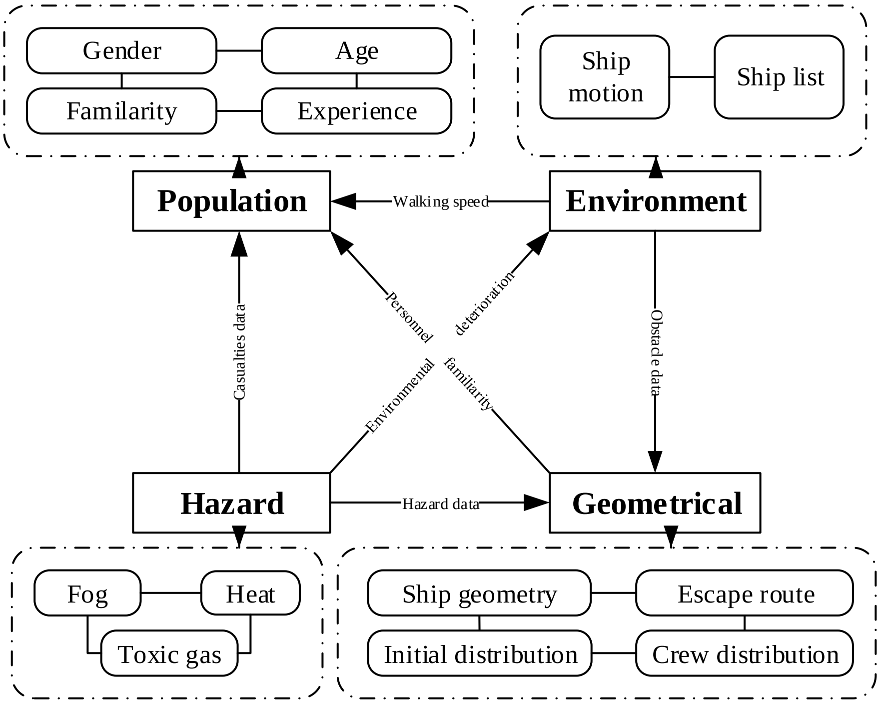


**Fig. 1 Analysis diagram of the influencing factors of passenger vessel evacuation.**

The following is a list of key factors influencing the uniqueness of passenger ship evacuation compared to land-based evacuations:

- *The uniqueness of the evacuation method.* Compared with land-based evacuation, one of the key features of ship evacuation is that life jackets should be worn and life rafts used to ensure the safe evacuation of the passengers and crew members [44, 49].

- *The complexity of the ship structure.* In terms of the structure, larger passenger vessels mean more complicated evacuation processes, having many decks and a limited number of exits. The passage stairs are mostly arranged inside the hull, and the exit is a muster station instead of a safety zone [36, 44].
- *The familiarity of personnel is low.* In terms of the population, the passengers of large passenger vessels are only on board for a relatively short amount of time, thus their familiarity with the ship structure and evacuation pathways is low. The path finding process therefore becomes complicated, and the possibility of evacuation path conflicts and congestion is increased [2, 17, 44].
- *The disadvantage of ship movement.* Human walking speeds and gaits will be affected by such factors as, the weather and sea conditions, ship motion and ship list. For example, a passenger's gait and speed is generally reduced to maintain balance on a swaying deck [34, 48, 50].
- *Human behaviour is complex and diverse.* Statistics shows that a number of passengers are accompanied by relatives and friends, and there will be gathering behaviour during an emergency situation. Subsequently, group evacuation can potentially increase the risk of congestion. Furthermore, passengers' perception and reaction to the emergency (pre-evacuation behaviour) differs greatly between day and night [28, 36].

### 2.2 The guidelines for passenger vessel evacuation

The guidelines provide two different methods of evacuation analysis: simple and advanced evacuation analysis. The former uses hydraulic flow system diagrams, treats passengers as the groups with the same characteristics, and uses simple formulas to calculate the entire evacuation time. The latter is a random analysis method using computer simulation to calculate the evacuation time by considering each passenger's characteristics including their age, gender, and capabilities as well as the specific distribution of the passenger vessel [25, 38, 51].

In recent years, due to the development of computing technology, evacuation models and simulations have been greatly developed, and the complex models and software enabling advanced evacuation analysis (*i.e.*, computer simulation) have received extensive attention [26, 50]. The guidelines divide the parameters used in advanced evacuation analysis into four categories: geometric parameters, population parameters, environmental parameters, and process parameters [38]. Geometric parameters mainly refer to the geometric layout of escape routes, obstacles and the distribution of the initial passengers and crew members. Population parameters mainly refer to gender, age, mobility, response time, and moving speed. Regarding the population parameters, the IMO gives the recommended population composition (age and gender), response time distribution, and the unhindered walking speed of different ages and genders in corridors and stairs [38]. In addition, the guidelines also give the evacuation performance standards for passenger vessels, and the calculation method is shown in Equations (1) and (2).

$$1.25(R+T)+\frac{2}{3}(E+L)\leq n \qquad (1)$$

$$(E+L)\leq 30\,\text{min} \qquad (2)$$

where, $R$ is the response time, which refers to the time from the evacuation alarm to the point when the evacuation movement starts; $T$ is the total movement time, counting the period from the time when everyone moves from their initial positions to the muster station; $(E+L)$ is the summation of boarding and launching times; and $n$ is the maximum allowable evacuation time. According to the guidelines, for Ro-Ro passenger vessels, $n$ is set as 60 minutes, and the maximum time for $(E+L)$ is 30 minutes.

After specifying the specific response time distribution, the obtained evacuation duration $(t)$ is the sum of the personnel response time and movement time. Considering the behaviours of passengers in the evacuation process, the duration of the simulation is a random variable. To obtain stable and reliable results, the guideline recommends that the simulation should be repeated at least 5 times for each population composition. The simulations should be sorted from low to high, and the 95th rank should be selected (*i.e.*, 95% of the personnel are safely evacuated) as the evacuation analysis time ( $t_{0.95}^{i}$ ) for simulation *i*. Finally, the maximum value of simulation *i*'s analysis time ( $t_{0.95}^{\max}$ ) is used for the evacuation analysis under this population composition [38].

### 2.3 Experimental study on passenger vessel evacuation

Large population and ship size, as well as the complexity of the ship structure, pose major challenges to passenger safety [51]. When compared with relatively mature experimental studies on land-based evacuation , the experimental research of passenger ship evacuation is scanty due to the changeable environment, limited by funding and safety issues [28, 40].

To provide empirical data of pre-evacuation stage for the evacuation analysis of passenger vessels, researchers from the Fire Safety Group of the University of Greenwich conducted three large-scale evacuation trials on Ro-Ro passenger ships and cruise ships. The trials used a semi-announcement (notifying people of the trials, but not the specific time) and were designed to collect passenger response times, establish acceptable personnel response times and evacuation time standards, as well as verify the effectiveness of the evacuation model. In these Ro-Ro passenger ship evacuation trials, the maximum response time was 402.4 s, the minimum time 0 s, and the average time 3.578 s (the standard deviation was 0.975). This project helped to fill the gap in understanding human performance during the evacuation of passenger vessels, especially passenger response time. The research results were submitted to the IMO in the form of proposals, and it was recommended that the response time distribution of personnel in the current guidelines can be improved [53-55].

Environmental factors such as high waves affecting the ship’s listing and motion are among the other factors affecting the analysis of passenger vessel evacuation. In order to reveal the impact of ship listing and motion on the personal evacuation process of passenger vessels, researchers carried out walking experiments on ship corridor simulators [27, 34] or moving ships [56, 57] to obtain the walking speeds of evacuees at different ship list angles or angular magnitudes of roll motion, so as to incorporate the reduction ratio of walking speed into the evacuation model under the ship listing and motion environment.

### 2.4 Simulation study of passenger vessel evacuation

Given that having a large number of people gathering in an experimental environment can be very costly and realistically difficult, the level of empirical knowledge of ship evacuation somewhat lags behind that of modelling and simulation [56, 58]. Evacuation modelling is devoted to developing simulation tools, finding evacuation congestion points, optimizing the ship layout, evaluating the effectiveness of evacuation plans, estimating the total evacuation time of various contextual conditions (such as the degree of congestion) on the site, and proposing a safe and effective management plan [34, 36, 58]. In view of the difficulty in obtaining ship evacuation data and the subsequent poor level data effectiveness, many ship evacuation studies in the literature mainly focus on computer simulations [26, 28, 59].

Based on the unique characteristics of passenger vessel evacuations, some researchers are committed to developing new evacuation simulation tools to analyse the evacuation process and predict the number of casualties to determine the evacuation possibilities of passengers in various disaster scenarios, modify the design of crowded points during the ship construction phase, and improve the safety and reliability of a ship [3, 26, 60]. Based on the original social force model, Kang *et al.* [61] incorporated the tendency force of pedestrians' downward sliding into the evacuation model on an inclined deck with coordinates suitable for the human body, and described the evacuation process of different shipwreck scenes. Xie *et al.* [62] used the polynomial chaotic expansion and nested sampling techniques to construct a new method based on alternative models to quantify the uncertainty of passenger escape time. A case study of a real passenger vessel was carried out to obtain the distribution of passenger movement time and identify the ship area that significantly affected passenger travel time. Sarvari *et al.* [16] designed an framework for marine emergency evacuation modelling, analysis and planning in which the emergency evacuation decisions of ferries are made through an integrated approach involving experimental design, simulation, statistical analysis and decision support systems (DSS). In order to accurately reflect the process of ship sinking in the simulation, Kim *et al.* [26] took the "Sewol" passenger vessel accident as an example and adopted a method of listing angle changing with time to reflect the ship's inclined state. Under the assumption that the captain gave the normal evacuation instruction, evacuation simulation analyses of three listing angles (0°, 30° and 52.5°) were carried out for the "Sewol" ship, the relationship between evacuation time and ship listing angles was compared, and the evacuation process and casualty number were also predicted and analysed.

However, the most complex issue in evacuation modelling is human behaviour. In the process of personnel emergency evacuation of passenger vessels, the safety awareness of evacuees is not high, and the perception of emergency wayfinding tools is poor [2], the performance of the crew members during the abandonment of the ship plays a key role in reducing the risk that may be caused by human error [15]. Tac *et al.* [5] developed a fuzzy decision method of trial evaluation (DEMATEL) to identify and quantify the factors affecting ship emergency preparedness in shipboard exercises, and analysed the influencing factors of pre-determined fire drill steps in an oil tanker at Sarkoy anchorage. Akyuz [15] proposed a fuzzy based success likelihood index method (SLIM) to analyse human errors in the process of abandoning ship, and evaluated measures to reduce human errors.

Although researchers have carried out a series of studies in the field of emergency evacuation of passenger ships, the IMO still encourages the member states to use the provided programmes and parameters to carry out evacuation analysis on existing passenger vessels, to identify congestion points and dangerous areas, and provide effective suggestions or scientific guidance [38]. In view of this, it is necessary to study the safety status of Ro-Ro passenger vessels along the high traffic routes such as the one between Yantai and Dalian; to evaluate the effectiveness of evacuation plans, ship layouts and crowd management strategies on the route; and to improve the safety of passenger ships. The contribution of this study to such issues is threefold.

(1) The demographic characteristics of passengers on the route from Yantai to Dalian were investigated, and compared with the population composition suggested in the guideline. It was pointed out that there were significant differences in the composition of passengers on different routes, and the population composition data was provided for the evacuation analysis of the passenger vessel on this route. Methodologically, it is new to incorporate population composition into evacuation modelling and to analyse the correlation between passenger population composition and the evacuation time.

(2) Based on FDS+EVAC, an evacuation model of the passenger vessel was newly proposed to study the influence of population composition and ship familiarity on the personnel evacuation process. It is suggested to investigate the population composition of one route or one type of ship before the evacuation analysis, so as to improve the accuracy of results for evacuation analysis.

(3) Combined with the existing geometric space conditions of the passenger vessel, tentative adjustments of the number of staircases at the bow and aft of the ship, as well as the width of the middle stairs were carried out, and the effect of stair layout on evacuation efficiency was studied to generate new managerial implications to guide geometric layout optimisation of this type of passenger ship.

## 3. Methodology and data

### 3.1 Data

The Bohai Bay (Yantai to Dalian) in China, possessing one major shipping route which is the longest cross-strait passenger route, is recognised as a high-risk maritime zone for the Ro-Ro passenger vessels. By the end of 2017, the number of Ro-Ro passenger vessels operating in the Bohai Bay was 23, with 32,340 passengers and 3,442 vehicle spaces. In 2017, Bohai Bay Ro-Ro passenger vessels transported 5.5 million passengers and 1.24 million vehicles, increasing by 6% and 9% from 2016, respectively

[28].

In this study, a questionnaire survey was first used to investigate the demographic characteristics of passengers and their familiarity with ships. This survey was conducted on the Ro-Ro passenger ship "Yong Xing Dao" of the China Ocean Shipping (Group) Company (COSCO)'s Shipping Passenger Line Co., Ltd. between Yantai and Dalian in the Bohai Bay. The details of the survey are presented in Wang *et al*. [28]. The survey was disseminated by 10 service staff on board from April 3 to May 18, 2019, lasting 45 days. The survey was approved by the Human Research Ethics Committee of Dalian Maritime University, and permitted by the captain and the company. After the passengers boarded the ship and sat down, this survey was conducted in a random, voluntary, autonomous, and anonymous manner. Before the survey, the research team trained the service staff so that passengers could be given detailed answers if they had questions.

For this survey, 1,800 questionnaires were disseminated, and a total of 1,550 questionnaires were received. After excluding questionnaires that were incomplete, 1,380 valid questionnaires were obtained, with a valid response rate of 89%. The statistical analysis was conducted to analyse the populations of this survey against the IMO guidelines and the result is shown in Table 1. There is a clear difference between the population composition of the guidelines and this survey. In addition, the results of this survey show that the probabilities that passengers on this route are familiar with the doors (excluding exits) and the muster station (exit) are 32.0% and 24.4%, respectively.

**Table 1 Population's composition (age and gender) of this survey compared with that of the guidelines.**

| Population groups – passengers | The Guidelines | This Survey |
|---|---|---|
| Females younger than 30 years | 7% | 29% |
| Females 30-50 years old | 7% | 16% |
| Females older than 50 years | 16% | 10% |
| Females older than 50, mobility impaired (1) | 10% | 3% |
| Females older than 50, mobility impaired (2) | 10% | / |
| Males younger than 30 years | 7% | 21% |

| | | |
|---|---|---|
| Males 30-50 years old | 7% | 13% |
| Males older than 50 years | 16% | 6% |
| Males older than 50, mobility impaired (1) | 10% | 2% |
| Males older than 50, mobility impaired (2) | 10% | / |

Note: Mobility impaired (1) refers to a group of people who have limited mobility but do not need help from others, while those in the mobility impaired (2) group need help from others.

### 3.2 Simulation tool

To conduct the advanced evacuation analysis of passenger vessels, there are many mature computer software packages in the literature. For instance, a non-exhaustive list of such software tools includes maritime EXODUS, EVI, SIMPEV, FDS+EVAC, and CityFlow-M [40, 54, 63-65]. FDS+EVAC, which was developed and maintained by the Finnish VTT Technology Research Centre [42] is selected to support the analysis in this paper. It is an agent-based evacuation simulation model and hence, fits the model of the interaction of individual's behaviour in crowd management in this work. Furthermore, it has passed the IMO tests by the IMO guidelines [42, 66]. FDS+EVAC treats each evacuee as an agent and introduces a "social force" to maintain a reasonable distance from walls and other agents. Its motion is represented by a series of motion equations, such as Equations (3), (4), (5), and (6). Each agent has its own unique evacuation strategies and attributes [42, 67].

$$m_i \frac{\mathrm{d}^2 \mathbf{x}_i(t)}{\mathrm{d}t^2} = \mathbf{f}_i(t) + \xi_i(t) \qquad (3)$$

where $\mathbf{x}_i(t)$ is the position of agent $i$ at time $t$, $\mathbf{f}_i(t)$ is the resultant force of the external environment acting on agent $i$, $m_i$ is the mass of agent $i$, $\xi_i(t)$ is a small random fluctuation force. The actual speed of agent $i$ is given by $\mathbf{v}_i(t) = \mathrm{d}\mathbf{x}_i(t) / \mathrm{d}t$ .

In Equation (4), it can be seen that the external environmental forces mainly include four parts. $\frac{m_i}{\tau_i}(\mathbf{v}_i^0 - \mathbf{v}_i)$ is the internal driving force of an agent, $\sum_{j \neq i}(\mathbf{f}_{ij}^{soc} + \mathbf{f}_{ij}^{c} + \mathbf{f}_{ij}^{att})$ is the interactions between agent $i$ and $j$, $\sum_{w}(\mathbf{f}_{iw}^{soc} + \mathbf{f}_{iw}^{c})$ is the interaction force between agent $i$ and the wall, $\mathbf{f}_{ik}^{att}$ is other interactions between agent *i* and the external environment.

$$\mathbf{f}_i = \frac{m_i}{\tau_i}(\mathbf{v}_i^0 - \mathbf{v}_i) + \sum_{j \neq i}(\mathbf{f}_{ij}^{soc} + \mathbf{f}_{ij}^{c} + \mathbf{f}_{ij}^{att}) + \sum_{w}(\mathbf{f}_{iw}^{soc} + \mathbf{f}_{iw}^{c}) + \sum_{k}\mathbf{f}_{ik}^{att} \qquad (4)$$

where, $\mathbf{v}_i^0$ is the initial speed of agent *i*, and $\tau_i$ is the relaxation time parameter, which is used to set the strength of the driving force so that the agent travels towards the exit at a specific speed. $\mathbf{f}_{ij}^{soc}$ is the social force between agent *i* and *j*, $\mathbf{f}_{ij}^{c}$ is the contact force between agent *i* and *j*, and $\mathbf{f}_{ij}^{att}$ is other interaction force between agent *i* and *j*, $\mathbf{f}_{iw}^{soc}$ is the social force between agent *i* and the wall, $\mathbf{f}_{iw}^{c}$ is the contact force between agent *i* and the wall.

$$\mathbf{f}_{ij}^{soc} = A_i e^{-(d_{ij} - r_{ij})/B_i}\left(\lambda_i + (1 - \lambda_i)\frac{1 + \cos\vartheta_{ij}}{2}\right)\mathbf{n_{ij}} \qquad (5)$$

where $d_{ij}$ is the distance between the centres of the circles of agents *i* and *j*, $r_{ij}$ is the sum of the radii of the circles, $\mathbf{n_{ij}}$ is the vector from agent *j* to agent *i*, $\vartheta_{ij}$ is the angle between the direction of the motion of agent *i* feeling the force and the direction to agent *j*, $A_i$ is the strength of the force, $B_i$ is the spatial extent of the force, and $\lambda_i$ is the parameter that controls the anisotropy of the social force.

$$\mathbf{f}_{ij}^{c} = (k_{ij}(r_{ij} - d_{ij}) + c_d \Delta v_{ij}^{n})\mathbf{n_{ij}} + \kappa_{ij}(r_{ij} - d_{ij})\Delta v_{ij}^{t}\mathbf{t_{ij}} \qquad (6)$$

where $\mathbf{f}_{ij}^{c}$ is the contact force between agents *i* and *j*, $k_{ij}$ is the radial elastic force strength, $c_d$ is a physical damping force, $\Delta v_{ij}^{n}$ is the normal velocity difference between the agents, $\kappa_{ij}$ is the strength of the frictional force, $\Delta v_{ij}^{t}$ is the difference in the tangential velocity of the contact circle between the agents, and $\mathbf{t_{ij}}$ is the unit tangential vector of the contact circle between the agents. The construction method of the force between the agent and the wall is similar to the force between the agents, and it needs no repetitions here.

Equations (3), (4), (5) and (6) describe the translational degrees of freedom of the evacuating agents, the rotational motion is also similar to translational motion, and the relevant description is not repeated here.

In FDS+EVAC, agents are divided into five types: adults, men, women, children, and the elderly. Each type of attribute has different default values, and users can change the response time and the distribution, walking speed, familiarity and other values for each type of person according to their needs [42]. Because of its flexibility and validity, the FDS+EVAC simulator is used in this study to perform the ship evacuation simulation and analysis. FDS+EVAC has two parts: the evacuation part EVAC and the fire part FDS. The versions of these two parts used in this study are FDS 6.6.0 and EVAC 2.5.2, respectively. FDS+EVAC can be used to predict the pedestrian dynamics under normal conditions or emergency evacuation during fires [63, 66].

Unknown or unfamiliar routes usually pose additional threats to pedestrians' safe evacuation. The familiarity with exits and herding behaviour are two very important factors that affect pedestrian route selection. The exit selection algorithm embedded in FDS+EVAC is based on the game theory and optimal response dynamics. Agents choose to observe the position of other agents and the degree of congestion before exiting, and then select the fastest estimated evacuation route [42]. Therefore, exit selection is modelled as an optimisation problem. In addition, the estimated evacuation time is not the only factor in choosing an exit. The embedded algorithm in FDS+EVAC also takes into account pedestrian familiarity with different exits, visibility near the exits, and fire conditions near the exits. The influence of these factors is taken into account by adding constraints to the evacuation time minimization problem [63, 66].

### 3.3 Procedure of the simulation-based experiment

The vessel "Yong Xing Dao" represents the main ship type serving on the Yantai and Dalian route, together with three other sister ships on the same route. The ship has a length of 167.5 metres, a width of 25.2 metres, and a total weight of 24,572 tonnes. It has a passenger capacity of 1,400 and a car capacity of 2,000, as well as 43 crew members and 27 service staff. The vessel travels between Yantai and Dalian once a day, including both outbound and inbound journeys. The ship has 10 decks, with passengers staying on the 7th deck and the front one third of the 8th deck. Specifically, there are 1,065 persons on the 7th deck and 335 persons on the 8th deck. Its geometric layout is shown in Fig. A1 of Appendix A. The simulated time is the total evacuation time, *i.e.*, the response time and movement time. The exits to which the agent moves are the doors to the ship assembly station, and it does not consider the effects of fire or the return behaviour of passengers to their cabins. It was assumed that all passengers were in their cabins at the beginning of the evacuation. As shown in Fig. A1 , the ship's exits are located on the 8th deck, of which there are four doors in the middle of the ship and one at the stern. The 7th deck is divided into three zones, and there are six staircases from the 7th to the 8th deck, among which there is one staircase in Zone 0703 (the bow of the ship), one in Zone 0702 (the middle of the ship) and four in Zone 0701 (the stern of the ship). It should be noted that there are two staircases at the front and two at the back of Zone 0701, and in the layout optimisation process, due to the limitations of the ship's available space, only the stairs at the back of Zone 0701 are adjusted in this study.

In the ship evacuation simulation, the input of the simulations was developed by manual coding, the grid size is 0.2m×0.2m, and passengers' exit selection type is active, that is, they actively observe the environment and look for the fastest exit. For several exits and doors, the exits and doors are defined with different ID identifiers. The movement speed of each corresponding population group was calculated using the values recommended by the IMO guidelines [38], as shown in Table 2. The response time of the corresponding population was calculated using the values obtained by the Gelea *et al.* [55] in the evacuation trials on Ro-Ro passenger ships, as shown in Section 2.3. The Chinese body shape refers to the national standard "National Standard for Chinese Adult Body Shape" [52].

**Table 2 The walking speeds of different population groups in different areas.**

| Population group | Flat terrain | | Stairs up | |
|---|---|---|---|---|
| | Min. | Max. | Min. | Max. |
| Females younger than 30 years | 0.93 | 1.55 | 0.47 | 0.79 |
| Females 30-50 years old | 0.71 | 1.19 | 0.44 | 0.74 |

| | | | | |
|---|---|---|---|---|
| Females older than 50 years | 0.56 | 0.94 | 0.37 | 0.61 |
| Females older than 50, mobility impaired (1) | 0.43 | 0.71 | 0.28 | 0.46 |
| Females older than 50, mobility impaired (2) | 0.37 | 0.61 | 0.23 | 0.39 |
| Males younger than 30 years | 1.11 | 1.85 | 0.5 | 0.84 |
| Males 30-50 years old | 0.97 | 1.62 | 0.47 | 0.79 |
| Males older than 50 years | 0.84 | 1.4 | 0.38 | 0.64 |
| Males older than 50, mobility impaired (1) | 0.64 | 1.06 | 0.29 | 0.49 |
| Females older than 50, mobility impaired (2) | 0.55 | 0.91 | 0.25 | 0.41 |

A flow chart of this study is shown in Fig. 2. A total of 9 scenarios were set up (A-I) to analyse the influences of the population, ship familiarity and staircase optimisation, respectively. Among them, Scenario C sets up 5 sub-scenarios, that is, 5 groups of different familiarity levels using probabilities. The comparison of Scenarios A and B was used to analyse the influence of population composition on evacuation, the comparisons of Scenarios B and 5 sub-scenarios of Scenario C were used to analyse the influence of familiarity levels on evacuation, and the comparisons of Scenarios B and D-I were used to analyse the influence of stair optimisation on evacuation. Table 3 shows the parameter setting and staircase layout of each scenario. Population composition was defined by &PERS. The number of personnel was set according to the proportion of personnel obtained from the IMO guidelines and the survey, as shown in Table 1, and the walking speed of personnel were adjusted based on Table 2 (Scenarios A and B). Personnel attributes were defined by DEFAULT_PROPERTIES, body circle diameter was defined by DIA-MEAN, shoulder circle diameter was defined by D-SHOULDER-MEAN, response time was defined by PRE_EVAC_DIST, PRE_MEAN, etc., and personnel walking speed was defined by VELOCITY_DIST, VEL_LOW, and VEL_HIGH. The familiarity of the personnel was defined by &EVAC. By setting KNOWN_DOOR_NAMES, KNOWN_DOOR_PROBS, the probability of the personnel familiarity with the ID identification of each exit and door was determined (Scenario C). The stairs were defined by &EVSS, the width of the middle stairs were adjusted by increasing or decreasing the width value (Scenarios D-F), the number of bow stairs were increased by copying the size of the existing bow stairs (Scenario G), and the number of aft stairs were increased by copying the size of the existing aft stairs

(Scenarios H-I).

After the simulation was completed, the total evacuation time and personnel evacuation variation tendency of each scenario were saved in an excel format file, and the data was sorted and analysed by Origin Lab. In the comparative analysis across the nice scenarios, the evacuation efficiency refers to the number of people who complete the evacuation at the same time, expressed by a curve slope (number of safely evacuated people/evacuation time). The larger the slope, the higher the evacuation efficiency is. The flow ratio refers to the number of people who are safely evacuated per unit time (persons/second), and is used to express the efficiency of people's evacuation through an exit or door.

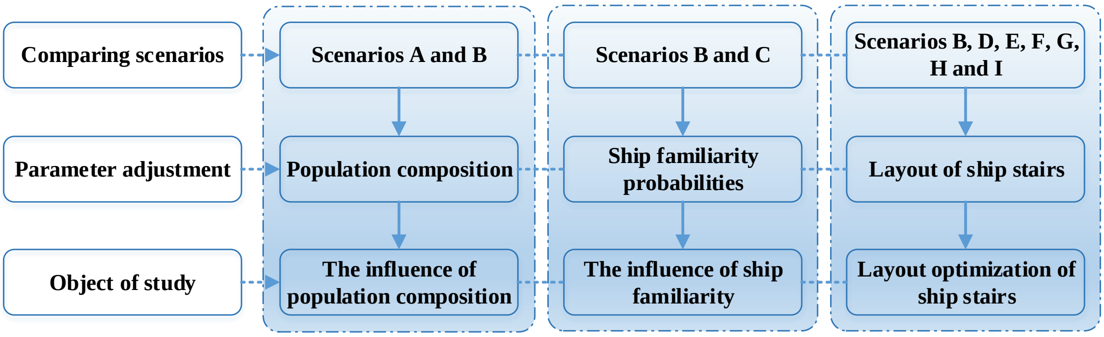


**Fig. 2 Flow chart of the research procedure.**

**Table 3 Details of different scenarios.**

| Scenarios | Population composition | Familiarity probabilities | Width of middle stairs (m) | Number of bow staircases | Number of aft staircases |
|---|---|---|---|---|---|
| A | IMO | 0.3 | 5.4 | 1 | 2 |
| B | Survey | 0.3 | 5.4 | 1 | 2 |
| C | Survey | 0.1/0.5/0.7/0.9/1.0 | 5.4 | 1 | 2 |
| D | Survey | 0.3 | 4.6 | 1 | 2 |
| E | Survey | 0.3 | 6.2 | 1 | 2 |
| F | Survey | 0.3 | 7.0 | 1 | 2 |
| G | Survey | 0.3 | 5.4 | 2 | 2 |
| H | Survey | 0.3 | 5.4 | 2 | 3 |
| I | Survey | 0.3 | 5.4 | 2 | 4 |

## 4. Results and discussion

### 4.1 Model validation

The evacuation performance index is deemed as the core that directly affects the number of casualties and the relief degree from disasters. Almost all maritime emergency evacuation analyses one always uses the evacuation time or assembly time as performance indicators [16]. Evacuation analysis is affected by various factors such as the geometric structure, population composition, and environmental factors [3, 28, 38, 51]. For validation purposes, by referring to the research of Sarvari *et al.* [16] and comparing the obtained results with the IMO guideline, the effectiveness of the simulation model is verified as follows. The description of the method of calculation in the guideline and its application to this passenger vessel is given in Appendix B.

Since the evacuation analysis of FDS+EVAC is a random process, during each evacuation analysis, the attributes and initial positions of the personnel are randomly assigned. The technical guide of FDS+EVAC recommends 12 simulations to observe the changes in the results [42]. Therefore, since the IMO guidelines recommend no less than five simulations and in order to obtain stable results, this study carried out 12 simulations for each scenario or sub-scenario. In Scenario A, the evacuation time of the last person is 777 s. As shown in Appendix B, the evacuation time is calculated as 805 s by using the real size of the passenger vessel. The difference of the obtained results between this simulation and IMO's evacuation assessment is 3.48%. According to the research result of Sarvari *et al.* [16], in which the absolute difference was 2.05%-19.82%, this result aids to verify the reliability of the established model.

The evacuation process is affected by many factors, such as interaction between people, interaction between people and structure, and passengers' familiarity with the vessel. It is necessary to verify if the trend of the evacuation time curve of the whole evacuation process in this study is consistent with the findings of similar physical structures and personnel compositions. In the study of Han [68], based on a similar physical structure and personnel composition (scenario B), the personnel evacuation simulation tool AnyLogic is used to establish the passenger ship evacuation model and simulate the personnel evacuation process, where the similarity and difference of parameters setting in Han [68] and this study are shown in Table 4. The comparison results are shown in Fig. 3. It can be found that the trend of the evacuation time curve of the whole evacuation process in this study is in line with the research results of Han [68]. However, it can be seen that the two curves in Fig. 3 have certain differences during 31 s and 317 s, which may be caused by the differences in geometric parameters or simulation platforms, as described in literature [69], and this needs to be analysed in future studies.

**Table 4 The similarity and difference of parameters setting in Han [68] and this study.**

| Category | Similarity | Difference | |
|---|---|---|---|
| | | Geometrical parameter | Simulation platform |
| Han [68] | Passenger vessel, population groups, walking speeds, familiarity probabilities, response time, etc. | 7$^{th}$ Deck | AnyLogic |
| This Study | | 7$^{th}$ and 8$^{th}$ Decks | FDS+EVAC |

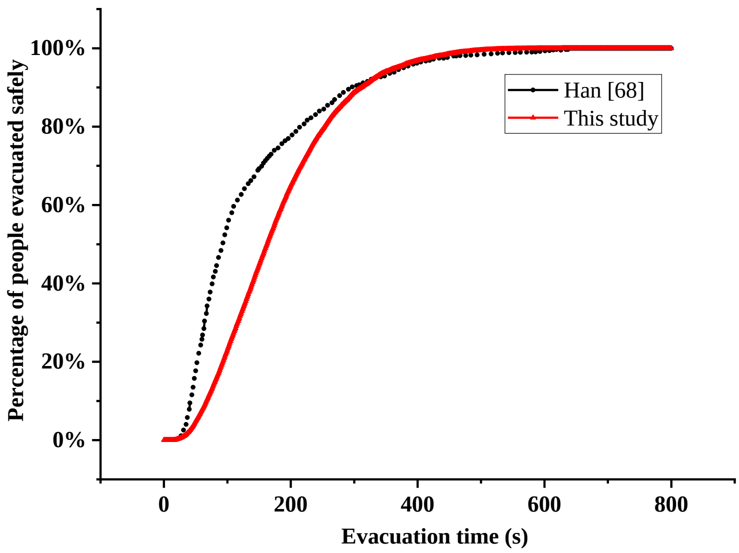


**Fig. 3 The simulation results of this study compared with previous study.**

### 4.2 The influence of population composition

The number of passengers and the population composition have important effects on the ship evacuation time [28, 51]. Evacuation studies of land vehicles [4] and aircrafts [4, 9, 10] have revealed that demographic characteristics, such as gender, age, and waist circumference, have a significant impact on the evacuation process. According to the population recommended by the guidelines (Scenario A) and that obtained from this survey (Scenario B), 12 ship evacuation simulations of each scenario were carried out, and the average value of the evacuation time of the 12 simulations of each scenario was taken for comparative analysis. The results of the 24 simulations and their average values are shown in Fig. 4, the evacuation times of different groups of people are shown in Table 5. Once the curves tend to be parallel to the horizontal axis, the evacuation process is completed. The first parallel times of Scenarios A and B are the time to complete the evacuation, as shown in Fig. 4 and Table 5 where the evacuation times of Scenarios A and B are 777 s and 637 s respectively.

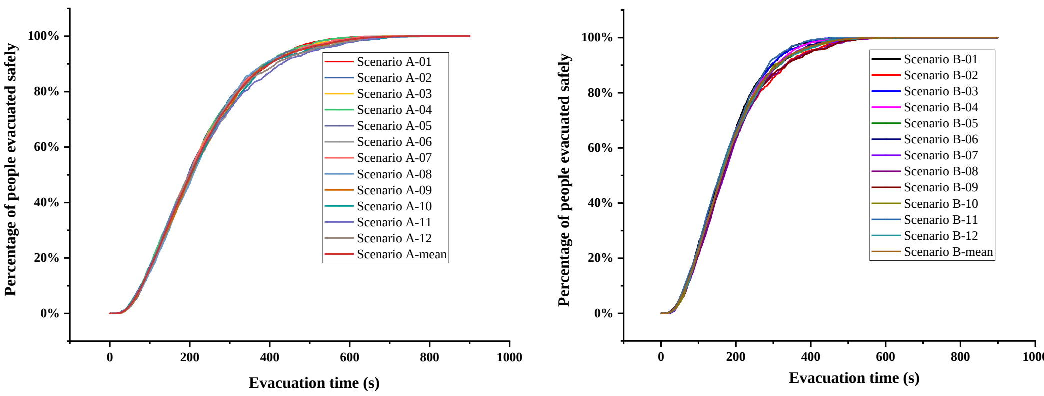


**Fig. 4 The evacuation times of this survey's population compared with the guideline.**

**Table 5 The evacuation times of different groups of people.**

| | Scenario A | Scenario B |
|---|---|---|
| First person | 15 s | 14 s |
| 95% person | 518 s | 404 s |
| Last person | 777 s | 637 s |

As shown in Fig. 4 and Table 5, the $t_{0.95}^{\max}$ of Scenarios A and B were 518 s and 404 s, respectively, indicating that the effects of different populations on the evacuation results are different. To analyse the significance of the difference, the Wilcoxon signed rank test in statistical analysis was performed on the average value of the 12 simulation results of Scenarios A and B using Equation (7), (8) and (9), respectively. The results (Z statistics and significance values) were $Z=-25.809$, $p<0.001$, indicating that the difference in the evacuation results obtained by the two scenarios is statistically significant.

$$Z_i = x_i - \theta_0, \quad \text{i=1, 2, } \cdots, n. \tag{7}$$

$$R_i = | Z_i | \tag{8}$$

$$W^{+} = \sum_{i=1}^{n} u_i R_i \ , \quad u_i = \begin{cases} 1 \ , \ Z_i > 0 \\ 0 \ , \ Z_i \leq 0 \end{cases} \tag{9}$$

where $x_i$ is the sample data, $\theta_0$ is median of sample data, $Z_i$ is the difference between the sample data and the median, $R_i$ is the absolute value of $Z_i$, and $W^{+}$ is the statistics for the signed rank sum test.

The guidelines give the recommended population, but the data is estimated by the IMO based upon data submitted by the member states. Moreover, even in the same country, ship passengers in different regions and routes may have different population compositions [28]. Considering that the composition characteristics of passengers have a considerable impact on the variation of evacuation time [9], in order to make evacuation simulation closer to the actual situation, it is recommended that before conducting the ship evacuation analysis, a targeted survey of the population composition of a specific route or a type of ship should be conducted to improve the accuracy of the evacuation analysis results.

### 4.3 The influence of ship familiarity

The evacuation path selection of passengers is based on their own perception and spatial memory [43]. In an emergency, the exit selection behaviour of a passenger is related to his or her own familiarity with the environment. Even if there is a closer evacuation route nearby, to ensure safety, people also tend to use their familiar routes [36, 63]. In this section, the passengers' familiarity (*i.e.,* ship familiarity) with the various doors (excluding exits) and assembly stations (exits) of the ship is adjusted to study the effect of different ship familiarity levels on the evacuation time. In the analysis process, the result associated with each familiarity level (probabilities) is the average of 12 simulation results. The ship familiarity of 0.3 is the result of this survey, which represents that the familiarity (probabilities) of passengers with each escape door is 32%, and their familiarity with each exit is 24%. Figs. 5-7 show the results of the ship evacuation under different familiarity levels.

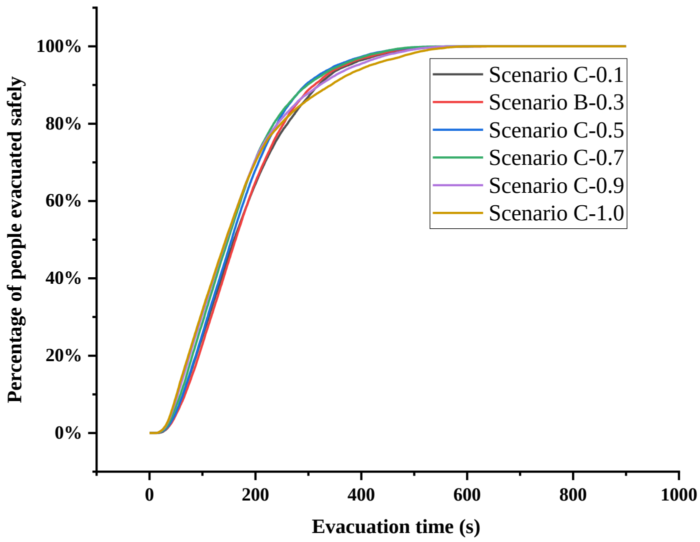


**Fig. 5 The variety of evacuation times and number of safe evacuees under different ship familiarity levels.**

As shown in Fig. 5, the evacuation results of different ship familiarity levels (probabilities) show similar trends. In the early stage of the evacuation process, compared with the ship familiarity of 0.1 and 0.3, there were more people evacuated when the ship familiarity was 0.9 and 1.0. However, as the evacuation process moves forward, this advantage gradually decreases. In the latter part of the analysis, the evacuation process is completed in the fastest time when the familiarity level is 0.7. However, the evacuation process takes the longest time when the familiarity level is 1.0. As shown in Fig. 6, different ship familiarity levels have little effect on the safe evacuation time of the first passenger, and they have a greater effect on the safe evacuation time of the last passenger. Regarding the average time for 95% of the passengers to complete the evacuation, the least time is required when the ship familiarity is 0.5 and the most when the ship familiarity is 1.0. Furthermore, when the time taken for the last passenger to complete the evacuation is calculated, the shortest evacuation time is obtained when the familiarity is 0.7 and the longest when the familiarity in 0.3.

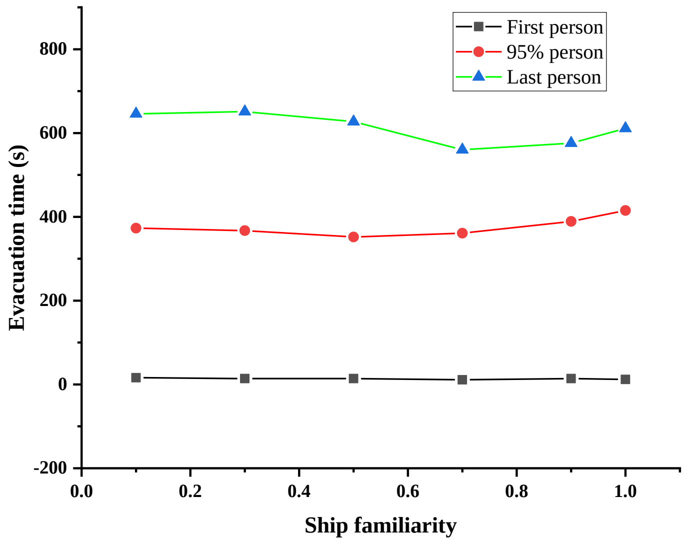


**Fig. 6 The relationship between the evacuation time and ship familiarity.**

Previous studies revealed that the familiarity with exits positively affect the evacuation results, and the lack of familiarity with ships contributes to the higher likelihood of human losses in maritime accidents [70]. The analysis results in Figs. 5 and 6 show that it is not true that the higher the passengers' familiarity with the ship, the less time it takes to complete the evacuation. A moderate degree of decision change is the strategy that will benefit the system most, as indicated in Haghani and Sarvi [71] on the evacuation of buildings and Kang et al. [61] on the evacuation of passenger vessels. In contrast, extreme decision change strategies (*i.e.*, "no change" and "everyone changes") are not considered to be optimal.

To further analyse the reasons behind this finding, the number of people evacuated through various exits over time and under different probabilities of familiarity was analysed, as shown in Fig. 7. The result shows that, when the ship familiarity level of 0.7, is compared with the ship familiarity levels of 0.9 and 1.0, the distribution of the number of evacuees at each exit is not balanced. For example, the number of people safely evacuated at Exit 201 (the exit with the most evacuees) is 468, and the number at Exit 101 (the exit with the least evacuees) is 166 when the ship familiarity level of 0.7. However, the number at Exit 201 (the exit with the most evacuees) is 562, and the number at Exit 102 (the exit with the least evacuees) is 158 when the ship familiarity level is 1.0. Because of this unbalanced distribution, there were too many people evacuating from Exit 201, which became the main reason for the delay of evacuation time, while other exits were idle in the final stages of the evacuation. Therefore, it is concluded that the familiarity is not a dominant/decisive factor affecting the evacuation efficiency, but the balanced use of exits is the real reason. In the study of personnel evacuation, the effect of familiarity should not be overemphasized, and the balance of exits must be considered appropriately. Only when all exits are fully and effectively used, the evacuation process can be completed quickly and safely.

Emergency preparedness is a key aspect of ship safety management. The study on passengers' safety awareness in the emergency evacuation process of ro-ro passenger ships shows that passengers are not familiar with the ship and have a poor perception of emergency wayfinding tools and procedures [2]. Although IMO regulations require that all personnel employed on board receive appropriate familiarization training, training on board is still ignored or delayed due to heavy workloads, time constraints or a lack of safety awareness [5, 72]. Therefore, it is recommended that ship staff should deliver safety information to passengers in the cabin through safety demonstration and safety information cards, and evacuation knowledge to passengers through safety demonstration in the seating area [2], so as to enhance passengers' familiarity with different exits of the ship, and guide passengers to use different doors or stairs evenly. In addition, the results of this study can be incorporated into the company's training courses for Ro-Ro passenger vessels, so that the crew members and staff can understand the behaviour and response of passengers, and make use of the existing resources to improve the familiarity of passengers with different evacuation exits of the ship, so as to improve the emergency response capacity of passengers, better lead and guide passengers to evacuate safely [5, 72].

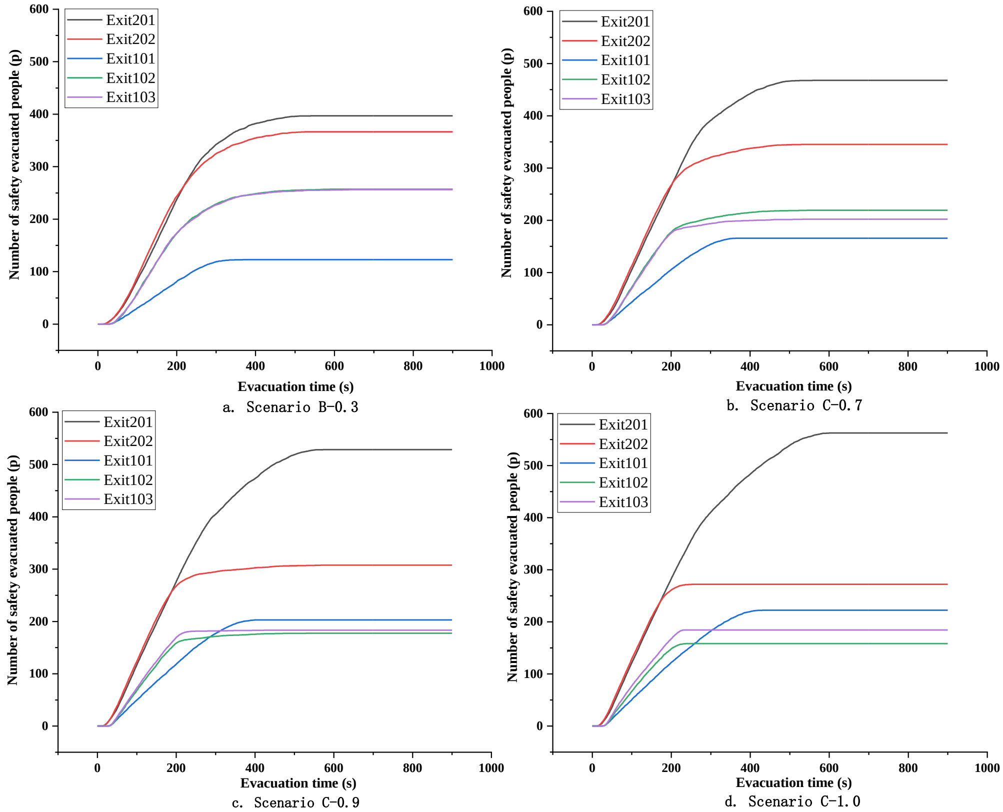


**Fig. 7 A variety of evacuation results for different exits under different ship familiarity levels.**

## 4.4 Layout optimisation of ship stairs

Passenger ship design is a complex process considering not only the technical requirements of marine navigation but also the needs of cabin capacity, safety regulations, and comfort [36, 43]. A staircase is a connecting part of a multi-story structure. It is very important to study the influence of the layout of staircases on evacuation procedures [63, 73]. Research related to passenger ship evacuation has focused on actual ship design, such as the location of the exits and the width of the walkway [48]. In the "Costa Concordia" accident, during the evacuation process, passengers were crowded on the stairs, and they shoved forward [36]. In view of the important impact of the staircase layout on the evacuation results, this section compares and analyses the impacts of different staircase layouts on the evacuation results to optimize the ship's staircase layout.

The average values of 12 simulation results for different scenarios are shown in Figs. 8 and 9. Fig. 8 shows that the difference in the personnel evacuation time between Scenarios B, D, E and F is small. It also shows that the evacuation time and the evacuation efficiency are almost equal. Similarly, the difference in the personnel evacuation time between Scenarios H and I is also small. The analysis in Fig. 9 shows that the time for the first person to complete the evacuation is basically the same under different conditions; adjusting the size of the staircase in the middle of the ship alone (Scenarios D, E and F), or adding 2 staircases separately at the stern of the ship (Scenario I), has little effect on the overall evacuation results. Table 3 shows different numbers of staircases per scenario. However, the difference in the evacuation times between Scenarios B and G (additional staircase at bow) is large. The average time for 95% of the passengers to complete the evacuation in Scenarios G (317 s) is 13.6% less than that in Scenario B (367 s). For all passengers, the evacuation time is reduced by 9.7% in Scenario G (588 s) compared to Scenario B (651 s). This shows that adding a staircase at the bow of the ship can significantly improve the evacuation efficiency and reduce the evacuation time. The comparison of Scenarios G and H shows that adding a stairway at the stern can reduce the time for all passengers to complete the evacuation by approximately 10%, but it cannot reduce the average time for 95% of the passengers to complete the evacuation.

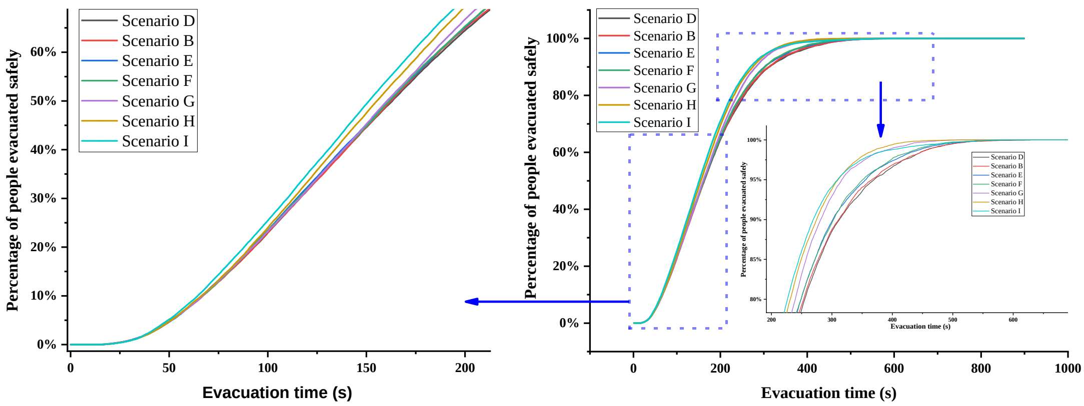


**Fig. 8 The evacuation time and the number of safe evacuees under different scenarios.**

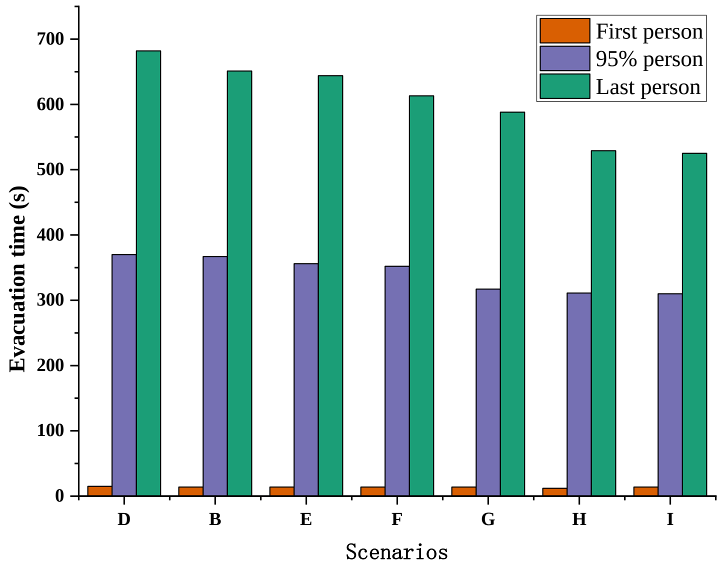


**Fig. 9 The relationship between the evacuation time and the optimized ship layout.**

It can be seen from Fig. 9 that the time of the last person to complete evacuation is about 250 s longer than that of 95% people, which is caused by the different time distribution of passengers to take actions after hearing the evacuation alarm in the pre-evacuation stage. For example, Galea *et al.* [53-55] showed that the maximum response time of personnel was 402 s. In view of the significant influence of response time on the evacuation time, in the existing drill practice or emergency evacuation activity, ship management or emergency evacuation on-scene command should fully realize this phenomenon, urge passengers to start evacuation as soon as possible through the public address system or staff to reduce evacuation delays caused by passengers packing or hesitation.

To understand the changes in the evacuation process after adding a staircase at the bow of the ship, the overall evacuation flow rate and the flow rate in Zone 0703 under the conditions of Scenarios B and G were plotted, as shown in Figs. 10 and 11. Figs. 10 and 11 show that adding a staircase at the bow of the ship can effectively improve the evacuation efficiency of Zone 0703. Passengers in Zone 0703 complete the evacuation by 130 s quicker, which not only eases the congestion of the single staircase, but maintains the overall evacuation flow rate at a relatively high level during the period of

170-260 s, thereby reducing the overall evacuation time.

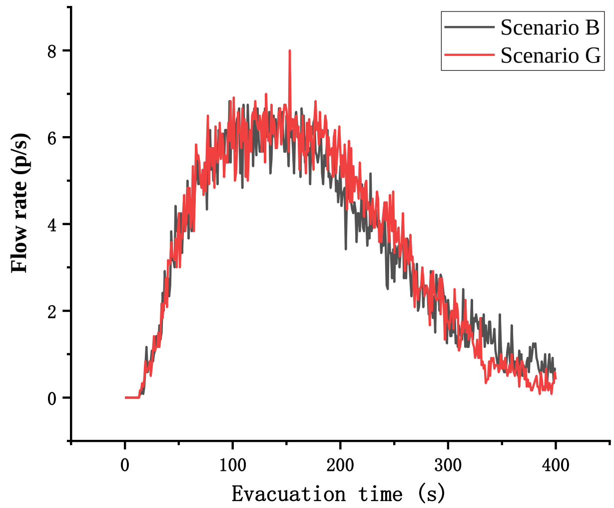


**Fig. 10 The flow rate of the total evacuation between scenarios B and G.**

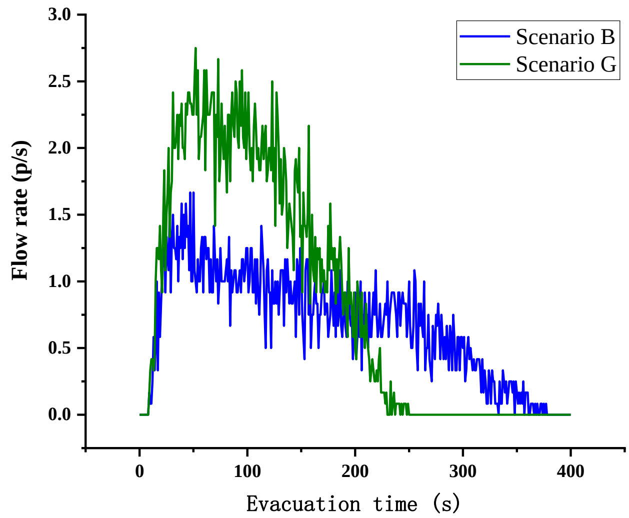


**Fig. 11 The flow rate of area 0703 between scenarios B and G.**

Based on the above analysis results, it is recommended that when the layout of the ship or similar ships is adjusted, a staircase can be added at the bow of the ship to improve the evacuation efficiency in an emergency. Similarly, it is recommended to consider adding a staircase at the stern of the ship to reduce the evacuation time for all passengers. Furthermore, considering the size of the space and the initial construction costs, the size of the staircase in the middle of the ship is appropriate, and there is no need to increase its size. It has to be noted that this layout optimisation can provide useful insights for naval architectures to consider in the future. However, this study does not analyse the ship's strength and ship ergonomics caused by such structural adjustment. Therefore, in the structural adjustment process of the ship, such factors as evacuation efficiency, ship structure, ship ergonomics and ship space conditions should be comprehensively considered.

The IMO Model Course (1.29) points out that newly assigned crew members should be familiar with emergency responsibilities before the voyage, and that passengers should be given practical guidance in the event of an emergency on board, as well as the possible evacuation and congestion situation in the existing ship layout, in order to take the appropriate emergency management measures [72]. This safety training is important to improve safety so that responsible crew members can effectively guide passengers in times of panic and improve the effectiveness of evacuation plans [5, 17]. Therefore, under the existing staircase layout, ship managers and staff are advised to guide passengers in Zone 0703 during evacuation training or trial activities to make full use the staircases in Zone 0702 during the evacuation to avoid overcrowding at the stairs in Zone 0703.

## 5. Conclusions

In the event of a serious passenger ship accident, an evacuation is the last resort to minimize the consequences of the accident. Emergency evacuation relies on good ship design (optimized exit and staircase layout), organization on board (training and drills) and operational practice (emergency task assignment and crowd management). It is of great significance to improve passenger ship design and develop effective evacuation plans by simulating emergency evacuation processes and estimating the overall evacuation time.

In the field of personal evacuation of passenger vessels, the current research overlooks the effect of population composition and ship familiarity on the efficiency of personal evacuation, this study investigated the effects of a Ro-Ro ship's passenger population composition and ship familiarity on safe evacuation. Utilising the FDS+EVAC evacuation simulation software, an evacuation simulation model of a Ro-Ro passenger vessel was developed to analyse the impact of population parameters and ship familiarity on evacuation time. The analysis shows that various population compositions significantly affect the evacuation time. It is recommended that before conducting a ship evacuation analysis, the population composition onboard the vessel should first be investigated in order to improve the accuracy of the evacuation analysis results. It is not necessarily true that passengers being more familiar with the ship will result in a shorter period of evacuation time. Yet, when passengers' evacuations are analysed, the effect of ship familiarity should not be overemphasized, and the issue associated with passengers' use of exits should be considered in a balanced manner. The analysis of the influence of different staircase layouts on the evacuation results shows that adding a staircase at the bow of the ship can reduce the average time for 95% of the passengers to complete the evacuation by 13.6%, and adding a staircase at the stern can reduce such time by 10%. It is not recommended that the size of the staircase in the middle of the ship is adjusted.

This study has provided some valuable insights in the context of passengers' evacuation in a Ro-Ro ship. It is worth noting that there are some limitations in this research. Firstly, the duration of the survey carried out in this study may be extended to enhance the credibility of the research findings, and the sample size may need to be further expanded to more accurately analyse the population composition and ship familiarity on this route. Secondly, this study does not consider the impact of a hazard (*e.g.* fire) on the evacuation, which can be a potential area for future research. Thirdly, the result of layout optimisation is only applicable to one specific ship/one ship type. Finally, in view of the limited availability of empirical data, this study does not consider the impact of operational environments (*e.g.* rogue waves and their effect on ship motion) on the evacuation.

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**Disclaimer**

The authors are solely responsible for all the views and analysis in this paper. This paper is the opinion of the authors and does not represent the belief and policy of their employers.

## Appendix A: The layout of Ro-Ro passenger vessel

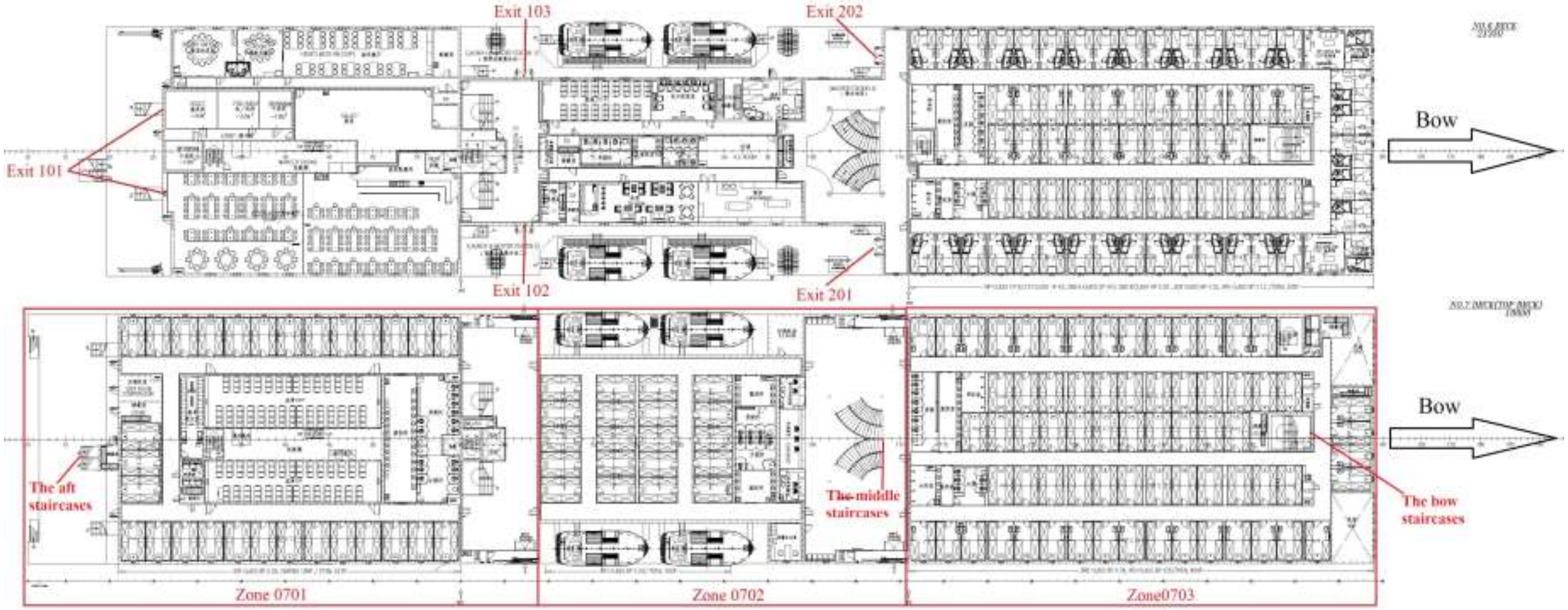


**Fig. A1 The geometry of the 7th and 8th decks of Ro-Ro passenger vessel.**

## Appendix B：Evacuation time formulations in IMO guideline and their application

The method to calculate the response time and travel duration in the IMO guideline can be shown as Equation (B1).

$$\begin{aligned} T &= A+T_I = A+(\gamma+\delta)*(t_F+t_{stair}+t_{deck}+t_{assembly}) \\ &= A+(\gamma+\delta)*(\frac{N}{F_s*W_c}+\frac{L_{stair}}{V_{stair}}+\frac{L_{deck}}{V_{deck}}+\frac{L_{assembly}}{V_{assembly}}) \end{aligned} \qquad \text{(B1)}$$

In the above, $T$ is the sum of response time and travel duration, $A$ is the response time, $T_I$ is the highest travel duration, $\gamma$ is the correction facto, $\delta$ is the counter-flow correction factor, $t_F$ is the flow duration, $N$ is the number of persons to move past a particular point in the egress system, $F_s$ is the specific flow of persons, $W_c$ is the clear width, $t_{stair}$ is the stairway travel duration of the escape route to the assembly station, $L_{stair}$ is the stairway travel length of the escape route to the assembly station, $V_{stair}$ is the speed of persons for stairs (up/down), $t_{deck}$ is the travel duration to move from the farthest point of the escape route of a deck to the stairway, $L_{deck}$ is the travel length to move from the farthest point of the escape route of a deck to the stairway, $V_{deck}$ is the speed of persons for travelling on decks, $t_{assembly}$ is the travel duration (s) to move from the end of the stairway to the entrance of the assigned assembly station, $L_{assembly}$ is the travel length to move from the end of the stairway to the entrance of the assigned assembly station, and $V_{assembly}$ is the speed of persons to move from the end of the stairway to the entrance of the assigned assembly station.

In the process of calculating the evacuation time, A, ϒ and δ are considered as 300, 2 and 0.3 with respect to day scenario (Case 1) in the IMO guideline, respectively [16, 38]. Speed parameters are received and interpolation calculated from tables in the IMO guideline [38]. The evacuation route for passengers travelling from the bow of the 7$^{th}$

deck through the middle staircase to Exit 201 or Exit 202 in the 8th deck is regarded as the longest evacuation route, calculated by multiple routes. According to the parameters above, evacuation time is obtained as follows:

$$t_F = [96/(1.00\times1.6)] = 60.00 \text{ s}$$

$$t_{stair} = (3.72/0.44)\times6 = 50.73 \text{ s}$$

$$t_{deck} = (31.5/0.91) = 34.62 \text{ s}$$

$$t_{assembly} = 7.4/0.1 = 74.00 \text{ s}$$

$$T = A + T_I = 300 + [(2+0.3)\times(60.00 + 50.73 + 34.62 + 50)] = 804.51 \approx 805 \text{ s.}$$

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