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# A quantitative study of the factors influencing human evacuation from ships

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ABSTRACT

Due to the constraints of various factors influencing human evacuation on board, it remains a challenging problem to accurately quantify the impact of these factors on the evacuation process. To analyse the multiple influential factors of human evacuation from ships, a specific framework based on orthogonal experiments is proposed in this paper to comprehensively investigate the impact of multiple factors on the evacuation time and the efficiency of the evacuation process. Heeling angles, unavailable stairs, and priorities of evacuees are identified as influential factors according to the characteristics of human evacuation from ships. The analysis results show that the heeling angle has a very significant effect on both evacuation time and efficiencies, and the efficiencies decrease as the heeling angle increases. Unavailable stairs also have a significant effect on evacuation results, the magnitude of which depends on the number of stairs nearby. While the effect of priorities of evacuees on evacuation results is relatively less important, it can be found that priority evacuation of pedestrians with impaired mobility will aid to achieve optimal evacuation results. In conclusion, the findings of this study can help managers quickly develop effective evacuation strategies in emergencies to further improve the safe operation of passenger ships.

## 1. Introduction

As the number of tourists choosing water sightseeing increases, the large-scale construction of passenger ships especially luxury cruises have become a major development trend. In this case, entertainment facilities onboard have gradually been enriched while most structures have increased in size and complexity, providing a more enjoyable experience to passengers (Chan et al., 2023; Wang et al., 2023a). However, it often leads to a more complex layout, which may increase the evacuation risks, especially in an emergency. Therefore, to minimize the evacuation risks, managers have to develop effective response plans for all possible emergencies (Wang et al., 2020). In general, passenger ships are prone to a wide range of hazards due to extreme factors of uncertainty and the constantly changing marine environments, as shown in ship accidents such as the Sewol and Costa Concordia tragedies, which resulted in serious casualties and property losses (Valcalda et al., 2022). In most ship accidents, improper organization and poor evacuation arrangements always lead to a delay of evacuation and serious disaster consequences, which also reflects that without a proper evacuation strategy, the evacuation process in emergencies can be inefficient and even lead to serious consequences (Kim et al., 2019, 2020; Sarvari et al., 2019; Wang et al., 2021a, 2021c).

With the continuous occurrence of passenger ship accidents, evacuation as the most important stage to ensure the safety of passengers onboard, has gradually attracted the attention of all fields of society (Christensen et al., 2022; Puisa, 2021; Shafiee and Animah, 2022). The International Maritime Organization (IMO) published the first edition of evacuation analysis guidelines for Ro-Ro passenger ships in 1999, and has revised the guidelines in recent decades to further improve the operational safety level of passenger ships. Currently, the latest edition

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of the *"Revised Guidelines for Evacuation Analysis for New and Existing Passenger Ships"*, (hereinafter referred to as the *"Guidelines"*), was approved by the IMO's Maritime Safety Committee (MSC) at its 96th meeting in 2016 (IMO, 2016). Although the latest edition of the *"Guidelines"* provides standard parameters and detailed analysis for ship evacuation, there is still a large space to supplement due to limited experimental data, especially for valid data in extreme cases (Arshad et al., 2022). Generally, it is a common phenomenon that a ship becomes a listed platform after accidents such as grounding, which is also the most obvious feature different from the land-based evacuation (Liu et al., 2022a). Evacuation in an inclined scenario suffers from many influential factors, however, due to the safety and cost issues of the experiment, it is impossible to reproduce the serious inclination and large-scall evacuation scenarios (Yue et al., 2022). Therefore, the MSC encourages member states to pay more attention to passenger ship evacuation, especially in the evacuation from heeled ships, so as to supplement more detailed behaviour parameters and formulate more specific evacuation strategies.

With the deepening of research, researchers gradually realize that it is very challenging to conduct real-time and effective risk assessment for the human evacuation process from heeled ships. A large and growing body of literature over the past two decades has investigated the influence of variations in angles of heel (Fang et al., 2022a), evacuation route planning (Li et al., 2019), interactions between pedestrians (Ni et al., 2018), and safety equipment and exits on board on evacuation efficiency (Wang et al., 2022a). Although most of the existing studies of human evacuation from heeled ships take the angle of heel as a variable to explore its influence on human behaviour, walking speed or moving time, it cannot directly provide suggestions for improving evacuation efficiency from a systematic perspective (Sun et al., 2018b). As a rule, it is difficult to achieve the performance evaluation of the evacuation system through the quantification of a single factor on a single index, which leads to the inability to form an effective evacuation management strategy based on an actual situation (Wang et al., 2023b). Therefore, how to formulate an effective evacuation strategy in an emergency has become a core safety issue of passenger ships at present.

In nature, human evacuation on board is a complex process, especially when a ship is heeling, the passengers become nervous and show heterogeneous behaviour. Meanwhile, the heeling ship can easily lead to a series of secondary hazards such as flooding and unavailable gangway (Xie et al., 2022). However, most of the existing studies of human evacuation from ships focused on one of the influential factors, and the scenarios were usually set to quantify the impact of a single factor on evacuation (Fang et al., 2022b; Kim et al., 2020; Liu et al., 2022b, 2022c). The comparison between the previous studies and this study is shown in Table .1. Based on full-size human evacuation from ships, the previous studies analysed the influential factors affecting the evacuation efficiency, and mostly used total evacuation time (TET) as an evaluation index. However, few of them mentioned the secondary hazards and human behaviour caused by heeling ships. In addition, occupant pass situation for ship (OPSS) is an index proposed in this study, which can not only reflect the utilization of the ship's facilities by evacuees during the evacuation process, but also be used as a quantitative parameter when developing ship evacuation strategies or optimizing ship layouts. Therefore, to evaluate the impact of ship heeling angle, secondary hazards, and competition behaviour of passengers on evacuation efficiency, three evaluation indexes, TET, mean congestion time (MCT), OPSS are all employed in this work to quantify the impact of these key factors on evacuation results.

Therefore, to analyse the complex process of human evacuation from ships, an innovative framework has been proposed to investigate the impact of multiple factors on evacuation results. Based on this framework, stakeholders such as ship managers/operators can fill in the factors that affect evacuation in different scenarios and systematically analyse the interaction between influential factors and evacuation results. The conclusions can directly provide the key factors that affect evacuation to managers and help them to rationally formulate evacuation strategies. In addition, heeling ship and secondary disaster caused by heeling are used as an example, and combined with different levels of human competitive behaviour, those three indexes that can describe the overall evacuation results and efficiency are used to quantify and rank different influencing factors. The rest of this study is organized as follows. Section 2 describes the details of the methodology and influential factors. It is followed by Section 3 in which a simulation model is constructed and the parameter settings of a case study are explained. In Section 4, the results derived from orthogonal experiments are analysed and discussed. Finally, a conclusion is summarized in Section 5.

## 2. Methodology

The flowchart in Fig. 1 explains the relationships between the analysis processes, which can demonstrate the proposed methodology in a logical way. Firstly, evacuation scenarios and the number of tests are designed according to the influential factors and the orthogonal experiments, details of which can be found in Sections 2.1 and 2.3, respectively. Secondly, the evaluation indices are determined to reflect the evacuation results in a comprehensive and detailed way in Section 2.2, and three indices applicable to the evacuation of ship personnel are introduced. Finally, the analysis methods of the orthogonal experiments are used to calculate the screening simulation test indices, see Section 2.4.

**Table 1**
Comparison of the previous studies.

| No. | References | Implementation | Scope | Evaluation indexes | Contributions |
|---|---|---|---|---|---|
| 1 | Yue et al. (2022) | Pathfinder | Heeling; Escape route | TET; Flow rate of the escape route | The passenger evacuation capability in specific accident scenarios was evaluated |
| 2 | Li et al. (2019) | Genetic algorithm | Evacuation route planning | The minimum clearance time | Evacuation performance was improved by assigning optimized level of service for facilities. |
| 3 | Kim et al. (2019) | Reciprocal Velocity Obstacles model | Heeling angle | TET | Predicted possible casualties at different heeling angles. |
| 4 | Fang et al. (2022b) | Anylogic | Heeling angle; crew's guidance | TET; Flow rate of exits | The participation of crew's guidance significantly accelerated the evacuation efficiency. |
| 5 | Wang et al. (2022a) | FDS + EVAC | Layout optimization | TET; Flow rate | Some suggestions were provided for the adjustment of ship stair layout. |
| 6 | Liu et al. (2022b) | Improved artificial fish swarm algorithm | Evacuation route optimization | TET; Waiting time | Congestion and slow evacuation were addressed by waiting and distribution methods. |
| 7 | Liu et al. (2022c) | Geographic information system | Ship spatial | TET; Evacuation accessibility | The spatial characteristics and potential spatial law information of ship passage evacuation capability were extracted. |
| 8 | This work | Pathfinder | Heeling angle; unavailable stairs; Priorities of evacuees | TET; MCT; OPSS | The key factors that affect the human evacuation on board are quantified through multiple indexes. |

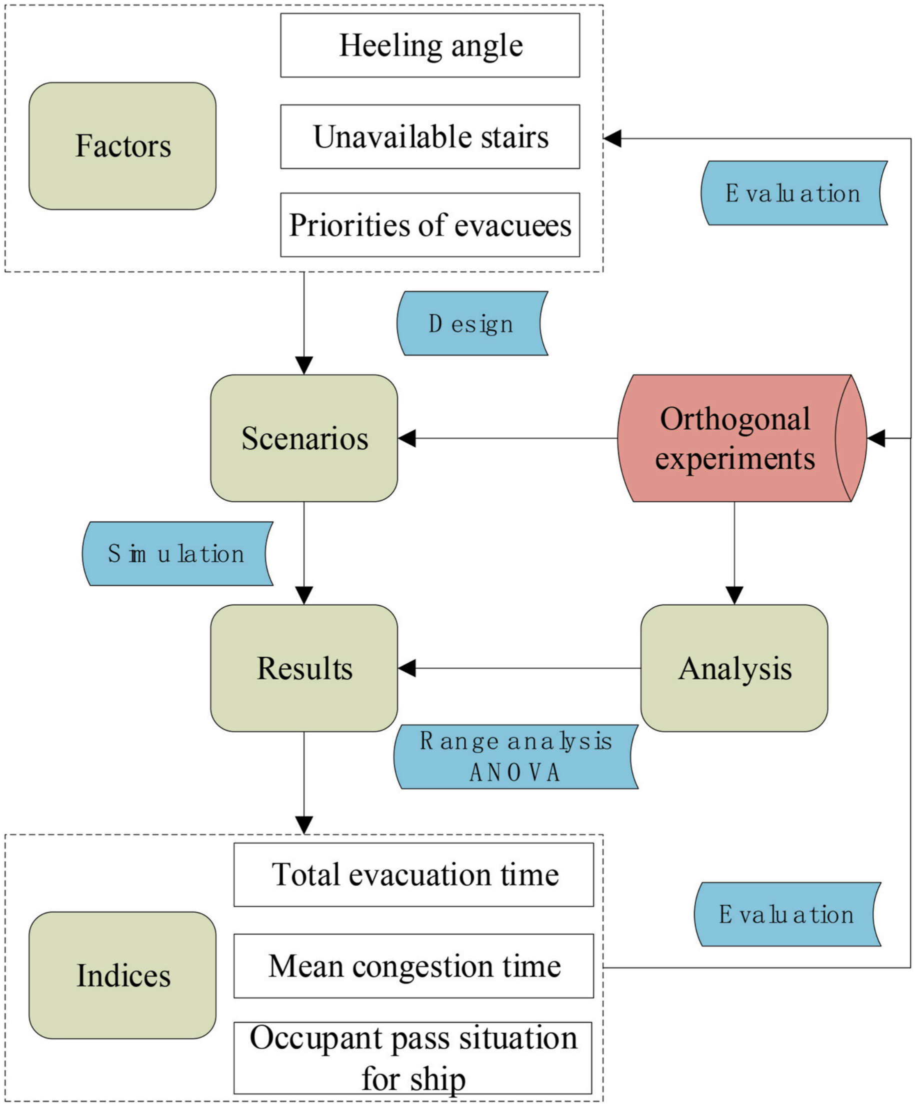


**Fig. 1.** The flowchart of the orthogonal experiments.

*2.1. Orthogonal experiments*

An orthogonal experiment is an experimental design method that studies multiple influential factors, and each influential factor has many kinds of classification. It does not require the development of an objective function, only selects some representative variables from many uniform tests based on an orthogonal table for analysis. An orthogonal table is a series of specification tables, denoted $L_n\ (r^m)$, where $L$ denotes an orthogonal table and $n$ is the number of rows in the orthogonal table, indicating the number of tests to be done. $m$ is the

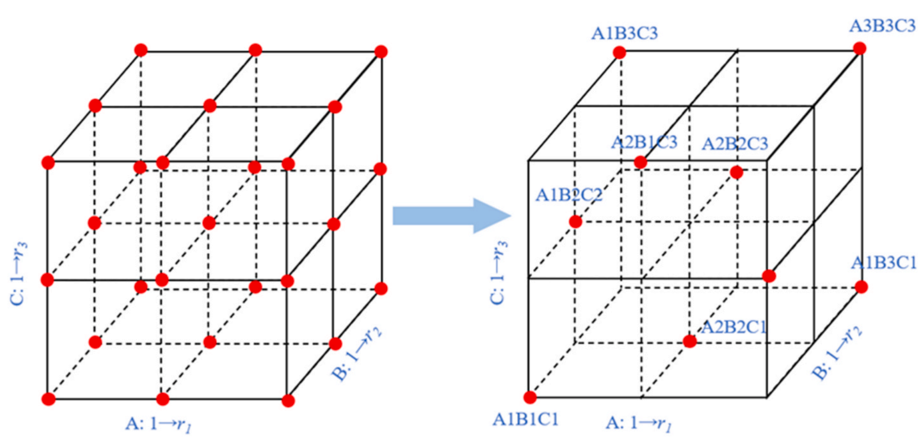


**Fig. 2.** The sketches for uniform and orthogonal experimental designs.

number of columns in the orthogonal table, indicating the maximum number of factors to be investigated. $r$ is the number of factor levels, indicating that this table can be arranged for $r$ levels of tests (Besseris, 2010).

The number of levels of each factor is equally assigned after screening, and the tests are arranged using the normalized orthogonal table to derive the sensitivity of parameters to the performance indices. The optimal hierarchical composition of the system parameters is then obtained by extreme difference analysis (Krishnaiah and Shahabudeen, 2012). There is an example of orthogonal experiments with 3 factors and 3 levels in Fig. 2. If a comprehensive experiment is conducted, 27 tests are needed, and only the most effective 9 tests need to be completed after screening using the minimum orthogonal table. The advantages of this approach are as follows:

a). A smaller number of experimental scenarios with strong representativeness can be selected evenly;
b). An optimal scenario can be derived from the results of the selected tests; and
c). more extra information can be obtained beyond the experimental results.

The orthogonal experiment has been popularized in the actual scientific research and production in industry, agriculture, and other fields (Li et al., 2020; Shehata et al., 2022; Wen et al., 2021). The quality of product design and development can be significantly improved by reasonable and scientific test design, and the optimal process conditions can be identified to enhance the final quality of the product (Guo et al., 2021; Xi et al., 2019). Considering the complexity of human evacuation from ships, the orthogonal experiment can simultaneously analyse the effects of multiple factors on evacuation results, and also can help managers to develop evacuation strategies more easily and effectively. The three characteristics of the orthogonal experiment make it attractive to human evacuation from ships. Firstly, there is no strict limitation on the number of influential factors, and this design can be used in the scenarios with and/or without the interaction between the influential factors. It means that potential factors such as secondary disasters caused by heeling ships and human likely behaviour can be analysed simultaneously without a strong assumption of mutual influence between the factors. Secondly, the orthogonal experimental method can ensure that all possible variations of the main influential factors are covered, especially when only one or two factors play a major role. This is important in exploratory work, such as the process of identifying key influential factors that affect human evacuation, and can be extremely helpful. Finally, the orthogonal experiment provides a chance to analyse results and draw specific conclusions through variance analysis. These quantitative results can visually demonstrate the importance level of each factor, to formulate the optimal evacuation strategies through factors ranking. Therefore, research on the evacuation onboard ships can also be carried out through orthogonal experiments to study the influence degrees of different factors on the evacuation results, so that the corresponding strategies can be proposed to improve the evacuation efficiency.

### 2.2. Evaluation indices of evacuation efficiencies

#### 2.2.1. Total evacuation time (TET)

TET represents the duration from the issuance of evacuation instructions to the arrival of the last occupant at assembly stations, which is the sum of response time and movement time (Lin and Wu, 2018). The response time is the duration from the initial emergency notification to the action the pedestrian starts to take, while the movement time is the process of the pedestrians from their starting point to the assembly station, which includes the pedestrians walking time and queuing time (Grandison et al., 2017).

#### 2.2.2. Mean congestion time (MCT)

Although the TET can directly quantify the evacuation result using time, it is only a macroscopic conclusion and cannot describe evacuation efficiency in detail. The evaluation of the evacuation process is often the fluidity of the pedestrian evacuation, which is determined by the congestion time of the pedestrians. Congestion was identified in the *"Guidelines"* by the following criteria (IMO, 2016):

1. Initial density greater than or equal to 3.5 persons/m$^2$; and
2. The difference between inlet and outlet of calculated flows is larger than 1.5 persons/s.

Congestion often occurs in narrow areas with small capacities, such as doors and stairs, where the number of arrivals to be evacuated exceeds the capacity, *i.e.* the quantified criterion is that the flow rate of the inlet is greater than the outlet by 1.5 persons/s, as shown in Eq. (1), where $\rho(t_i)$ is the density at time $t_i$, and $F_{\_in}(t_i)$ and $F_{\_out}(t_i)$ are the inlet and outlet of flows, respectively. Similarly, when a slow-moving pedestrian blocks the evacuation route, others behind him/her have to wait rather than cross directly (Zhang et al., 2020). In this case, the pedestrian may walk at a very slow speed and the duration of this movement is a direct indication of the evacuation efficiency during this period.

$$F_{\_in}(t_i) - F_{\_out}(t_i) > 1.5 \text{ pers} \Big/ \tag{1}$$

In order to quantify the congestion of an evacuation in detail, the MCT is used as an evaluation index for the evacuation efficiency, as shown in Eq. (2), where $CT_i$ is the total congestion time for the $i$th pedestrian and $N_p$ is the total number of pedestrians during the evacuation.

$$MCT = \frac{\sum_{i=1}^{N_p} CT_i}{N_p} \tag{2}$$

#### 2.2.3. Occupant pass situation for ship (OPSS)

Due to the complex structure of the ship layout and the confined space, the passageways are relatively narrow onboard ships. At the same time, passengers, as temporary residents onboard, are more likely to choose routes they are familiar with or follow the crowd to find a safe route (Li et al., 2019). It is an illustration that some common routes connecting public and living areas may be chosen by a large number of passengers as escape routes, while others that are less frequently used and inconspicuous but can also be safely reached at the assembly station are easily ignored by pedestrians (Wang et al., 2022b). This behaviour can lead to uneven evacuation efficiency at some exits and stairs, with some commonly used routes overloaded having more evacuation tasks than they could handle, while others are idle with only a small number of pedestrian passing through (Wu et al., 2018).

Therefore, quantifying the usage efficiency of exits is also significant for assessing evacuation results. In land-based evacuation studies, occupant pass situation (OPS) is often used to represent the usage of all exits (Hu et al., 2018). The calculation of OPS is shown in Eq. (3).

$$\text{OPS} = \frac{\sum_{i=1}^{n} (EET_{\max} - EET_i)}{(n-1) \times EET_{\max}} \tag{3}$$

where $EET_i$ is the time from the start of the evacuation to the last pedestrian passing the $i$th exit, $EET_{\max}$ is the maximum usage time for all exits and is generally equal to the TET, and $n$ is the number of exits.

However, for the human evacuation from passenger ships, pedestrians need to be summoned to the assembly station and then escape from the ships. At this point, it is no longer makes sense to evaluate the usage of the exits and the assessment of the use of stairs leading to the assembly station is more applicable to passengers' evacuation from ships

(Wang et al., 2022a). For an effective evaluation of the efficiency of the routes during onboard evacuation, OPSS is introduced to quantify the usage of stairs in cabins. Compared to the application scenarios of traditional OPS, the OPSS offers the following improvements:

a) Stairs are evaluated in OPSS instead of exits. For the special evacuation scenarios of ships, it is invalid to calculate the usage of exits because all exits are concentrated at assembly stations and their usage durations are very similar. As a result, the usage of stairs is evaluated as the subject of this study to provide a more accurate description of evacuation efficiency.
b) The evaluation parameter in the OPSS is the operation duration of each stair rather than the evacuation time of the last pedestrian leaving the stair, which is the period of time from the first pedestrian using the stair to the last pedestrian leaving the stair. Unlike the evaluation of the usage of exits, the stairs are used in a sequential order. Considering, for example, that stairs further away from the assembly station are assigned fewer evacuation tasks, only used at the beginning of the evacuation, however, the use of those close to the assembly station continues until the end of the evacuation. It is, therefore, more reasonable to use the duration of usage of each stair as an evaluation parameter.
c) In the calculation of OPSS, the usage efficiency of stairs for each deck is calculated separately and the result of OPSS is the sum of the stair usage efficiencies for all deck levels. As these stairs are not at the same level, the usage durations cannot be compared directly. As a result, it is necessary to compare the usage efficiency of stairs at the same level, *i.e.* on the same deck. In general, the stairs connected to the decks of the assembly stations have the longest duration of usage, and conversely, the further away from the assembly stations the deck on which the stairs are located, the shorter the usage durations of these stairs.

Eq. (4) is used to calculate OPSS, where $DET^{i}_{\max}$ is the longest duration of stairs usage on the $i$th deck, $DET_{ij}$ is the usage duration of the $j$th stair on the $i$th deck, $n_s$ is the number of stairs on the $i$th deck and $n_d$ is the number of decks. In contrast to the traditional OPS whose value interval is [0, 1], the OPSS is the sum of the stair usage efficiency for each deck, and it takes the value interval [0, $n_d$].

$$\mathrm{OPSS} = \sum_{i=1}^{n_d} \frac{\sum_{j=1}^{n_s}\left(DET^{i}_{\max} - DET_{ij}\right)}{(n_s - 1) \times DET^{i}_{\max}} \tag{4}$$

### 2.3. Influential factors

#### 2.3.1. Heeling angles

As a result of accidents such as collisions and groundings, ships tend to capsize due to constant external forces. In this process, ships may show different degrees of heel (Fang et al., 2022b; Sun et al., 2018a). The effect of heeling angles on walking speed has been studied in several literature (Fang et al., 2022a; Kang et al., 2019; Kim et al., 2019). However, the influence of a heeled ship on evacuation time has not been analysed, so a heeling angle is identified as an influential factor in the orthogonal experiment (Sun et al., 2018b; Wang et al., 2021b). Several heeling angles and their influence on individuals' walking speeds have been investigated in previous literature (Fang et al., 2022a) and the variation in individuals' walking speeds is large at these critical values (Azizpour et al., 2022). Therefore, several heeling angles are set with respect to the previous studies as shown in Table 2 (Fang et al., 2022a; Wang et al., 2021b).

#### 2.3.2. Unavailable stairs

4 scenarios are defined for the human evacuation from passenger ships in Annex 1 of *"Guidelines"* (IMO, 2016), where cases 1 and 2 are the primary evacuation cases for the pedestrians' distribution during day and night respectively, while cases 3 and 4 are secondary studies of cases 1 and 2, in which the stairs with the largest capacity are unavailable for consideration.

**Table 2**
Details of heeling angle for 4 levels.

| Level | Heeling angle | Description |
|---|---|---|
| 1 | 0° | Baselined scenario, in which pedestrians' speed is undiminished. |
| 2 | 5° | When the pedestrians walk downward in the heeling direction, the 5° angle of heel is considered to within their control, with a small increase in speed. |
| 3 | 15° | If pedestrians walk on the ship with an angle of heel of less than 15°, there is some attenuation of speed, but it does not have a significant impact on the TET. When angles of heel are larger than 15°, the individual's walking speed reduces significantly and the evacuation time increases sharply. |
| 4 | 25° | If the heeling angle reaches 25°, it is extremely challenging for pedestrians to walk, the walking speed decreases rapidly and the evacuation time increases exponentially. |

In land-based evacuation, pedestrians passing through the exits of the first floor are considered to have completed the evacuation, while the pedestrians on board first need to travel to the assembly stations before leaving the accident areas (Arshad et al., 2022). However, the assembly stations are always located on the open decks, which are not usually at the lowest or highest deck. This means that the assembly stations are not on the same deck as the cabins and entertainment areas. As a result, passengers have to walk through a series of stairs and corridors to reach their destinations while escaping on board (Spyrou and Koromila, 2020). It is necessary to consider the unavailable stairs mentioned in cases 3 and 4, however the impact of the unavailable stairs located at different decks on evacuation efficiency has not been systematically analysed.

In order to analyse the impact of the unavailable stairs at different decks, the vertical height between the unavailable stairs and the deck of an assembly station is used as a quantified indicator, as shown in Eq. (5):

$$D = \left| D^{\mathrm{th}}_{\mathrm{a-s}} - D^{\mathrm{th}}_{\mathrm{u-s}} \right| \tag{5}$$

where $D^{\mathrm{th}}_{\mathrm{u-s}}$ is the vertical height of the deck of unavailable stairs, $D^{\mathrm{th}}_{\mathrm{a-s}}$ is the vertical height of the deck of an assembly station, and $D$ is the vertical height difference between $D^{\mathrm{th}}_{\mathrm{a-s}}$ and $D^{\mathrm{th}}_{\mathrm{u-s}}$. If $D = 0$, it means that an unavailable stair and the associated assembly station are located on the same deck. When $D = n_d$, it is indicated that the difference of the layers is $n_d$. Table 3 describes in particular the four example levels of unavailable stairs.

#### 2.3.3. Priorities of evacuees

The *"Guidelines"* have different category parameters for the population's composition, including age, gender, physical attributes and response duration (IMO, 2016). It has been shown that the different compositions have impacts on the evacuation results in other fields (Hu et al., 2018). In particular, passengers with impaired mobility in restricted spaces tend to cause congestion due to their slow movement and without receiving assistance from others, and make the congestion

**Table 3**
Details of unavailable stairs for 4 levels.

| Level | $D$ | Description |
|---|---|---|
| 0 | 0 | Unavailable stair on the same deck as the assembly station. |
| 1 | 1 | Unavailable stair on the deck one level up or down from the assembly station. |
| 2 | 2 | Unavailable stair on the second deck up or down from the assembly station. |
| 3 | 3 | Unavailable stair on the third deck up or down from the assembly station. |

serious as others with higher speeds gather there (Xie et al., 2020).

In order to change the above-mentioned congestion, game theory and image recognition methods have been used in the existing studies to observe the details of this phenomenon and it has been found that the conflict between pedestrians for the target area can be effectively solved if they are divided into different walking priorities (Cao et al., 2021). This kind of pedestrian competition-waiting behaviour needs to be considered exhaustively in models, especially the automaton cellular model where some agents compete for the same grid (Ren et al., 2021). In order to highlight this phenomenon in the orthogonal experiment, the number of priorities of the evacuees is set as an influential factor, and the effect of different levels of priority on the evacuation results is numerically calculated. Considering the priority rights of elder, sick, and disabled passengers in terms of ethical values, the priority levels are divided as shown in Table 4.

### 2.4. Methods of analysis

For the screened tests, appropriate analytical methods should be selected to explain the influential factors of target indices, of which range analysis and analysis of variance (ANOVA) are widely used in orthogonal experiments (Wu and Hamada, 2011).

#### 2.4.1. Range analysis

Range analysis is an intuitive and concise method, which is mainly used to determine the sensitivity of factors to performance indices. $R$ is introduced to reflect the variation range of evaluation indices as the level of each influential factor changes, and is calculated as shown in Eq. (6), where $T_{i,j}$ is the mean value of the evaluation index of influential factor $i$ ($i = A_1, A_2, A_3, \ldots, A_m$) at level $j$ ($j = 1, 2, 3, \ldots, r$). $T_{i,j}$ can be calculated as Eq. (7):

$$R = \max(T_{i,j}) - \min(T_{i,j}) \tag{6}$$

$$T_{i,j} = \frac{x_{i,j}}{m} \tag{7}$$

where $m$ is the number of levels, $x_{i,j}$ represents the sum of all experimental results of influential factor $i$ at level $j$. For example, $T_{A1,1}$ indicates the average of all experimental indices when the level of influential factor $A_1$ is 1. In range analysis, the larger $R$ is, the more significant the influence of the factor on the indices, and the more important the influential factor is. Therefore, according to the range of these influential factors, the influence of factors on the indices is judged to be more or less (Li et al., 2020).

#### 2.4.2. ANOVA

Although range analysis has the advantage of being concise and intuitive, it cannot describe the errors. In order to accurately estimate the significance of each factor on the experimental results, it is necessary to use ANOVA for the orthogonal tests, especially for the experiment with the number of factors and levels greater than 3 (Calinski and Siatkowski, 2017).

Some parameters of ANOVA that should be determined, include the total sum of deviation squares $SST$, the sum of squares of single factor $SS_m$, the degree of freedom $f$, the mean square $MS$, and the $F$-value. The calculation details of these parameters are as follows:

$$SST = \sum_{k=1}^{n} (x_k - \bar{x})^2 = \sum_{k=1}^{n} {x_k}^2 - \frac{T^2}{n} = Q - P \tag{8}$$

$$\bar{x} = \frac{\sum_{k=1}^{n} x_k}{n} \tag{9}$$

$$T = \sum_{k=1}^{n} x_k \tag{10}$$

$$f_T = n - 1 \tag{11}$$

where $n$ is the number of total tests, $x_k$ is the result of the $k$th test, $T$ is the sum of all results, and $\bar{x}$ represents the average of the total results. The degree of total freedom $f_T$ is related to the number of tests. Then $Q$ and $P$ are assumed as $Q = \sum_{k=1}^{n} {x_k}^2$ and $P = \frac{T^2}{n}$ for the sake of convenience, respectively. $SST$ reflects the total difference of the results, and the larger $SST$ is, the greater the difference between the tests. Furthermore, the $SST$ is caused by two limitations, one is the level change of influential factors, and the other is the experimental error.

For the sum of deviation squares of a single factor, it can be calculated by Eq. (12),

$$SS_m = \frac{r}{n}\left(\sum_{j=1}^{r} {T_j}^2\right) - \frac{T^2}{n} = \frac{r}{n}\left(\sum_{j=1}^{r} {T_j}^2\right) - P \tag{12}$$

$$f_m = r - 1 \tag{13}$$

where $r$ is the number of levels of influential factor, $T_j$ presents the sum of the results of objective factor at level $j$, and the degree of factor freedom $f_m$ is $r$-1, as shown in Eq. (13). In ANOVA, the blank column in the table is error column, and the sum of deviation squares of errors $SS_e$ and the degree of error freedom $f_e$ are calculated in the same way as Eqs. (12) and (13).

Given that the above calculation can only explain the sum of deviations of each influential factor, it is necessary to find the $F$-value by the mean squares of factor and error to visualize the magnitude of the influence of each influential factor on the results. The $F$-value is calculated as in Eq. (14), where $F_m$ represents the F-value of factor m, $MS_m$ and $MS_e$ are the mean squares of the factor m and the error, respectively. The significance test for factors can be determined by the $F$-value. The critical value $F_\alpha$ ($f_m$, $f_e$) can be found from the F distribution table by using the given test level $\alpha$. If the $F_m > F_\alpha$, the factor m has a significant effect on the results. The greater the difference between the $F_m$ and $F_\alpha$ is, the greater the significance of the influential factor is. It is worth noting that if $MS_m < 2MS_e$ for factor $m$, the mean squares and the degree of freedom of the influential factor should be incorporated into the error to increase the significance of the results of ANOVA.

$$F_m = \frac{MS_m}{MS_e} = \frac{SS_m / f_m}{SS_e / f_e} \tag{14}$$

**Table 4**
Details of priorities of evacuees for 4 levels.

| Level | Number of priorities | Description |
|---|---|---|
| 1 | 1 | Same priority for all passengers. |
| 2 | 2 | Elder people (>50) with impaired mobility have first priority. |
| 3 | 3 | Elder people (>50) with impaired mobility have the highest priority, elder people (>50) without impaired mobility have the higher priority and others the lowest. |
| 4 | 4 | Elder people (>50) with impaired mobility have the highest priority, elder people (females, >50) without impaired mobility have the second higher priority, elder people (males, >50) without impaired mobility have the third higher priority and the rest have the lowest. |

## 3. Case study

### 3.1. Passenger ship construction

In order to illustrate the study approach and draw useful conclusions, a training ship MV *"Yukun"* of Dalian Maritime University in China is selected as the case and modelled in Pathfinder, as shown in Fig. 3. The

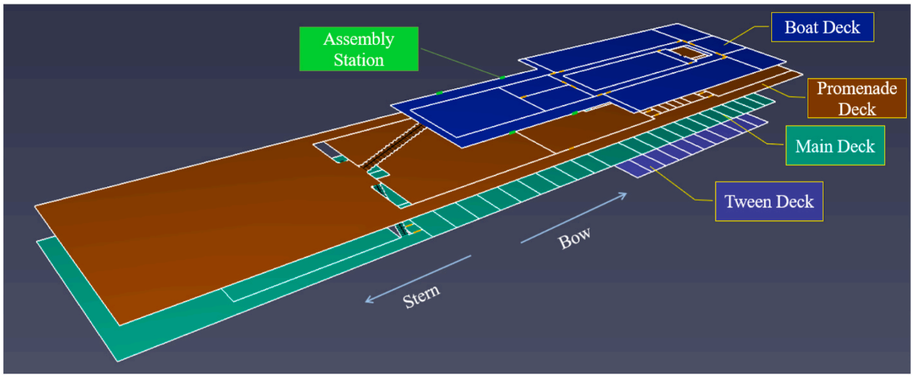


**Fig. 3.** The simulation model of MV "Yukun".

living area of this training ship is mainly on four decks: boat deck, promenade deck, main deck, and tween deck, which can accommodate 236 persons. Based on the functional characteristics of the cabins, some modules like the engine room and storeroom are not given in detail to facilitate the observation of the evacuation process. Meanwhile, the directions of bow and stern are also indicated by arrows in Fig. 3.

The assembly stations are set on the blue area in Fig. 3 which is the boat deck. Passengers need to arrive at the assembly stations to board the lifeboats to escape from the ship. The orange area is the promenade deck, mainly including the canteen, classroom, and a few single cabins, where only a few crews live. The green deck is the main deck, which contains 34 cadet rooms, three of which are two-bed rooms and the rest are four-bed rooms. In addition, some cadets live on the tween deck (violet area) which is the lowest deck, with a relatively small number of cadets living on the half of the deck near the bow and 72 persons at full capacity.

### 3.2. Parameters setting

For the operation of the decision rule database, two modes of behaviour, steering and Society of Fire Protection Engine (SFPE), are used in Pathfinder to control the movement of evacuees. As the steering mode is closer to reality, it is adopted in this study to allow pedestrians to follow their assigned route, which is a quadratic B spline interpolation curve of the current position at each waypoint. In this mode, the pedestrians are allowed to deviate from the route but still proceed toward their endpoint (Sun et al., 2019).

In the evacuation simulations, appropriate parameter settings can play a crucial role in the accuracy of the results, after analysing and studying the data from the drill and observation, information on population's composition, response duration, and walking speed of passengers have been suggested in the *"Guidelines"* (IMO, 2016). In this study, the demographic parameters presented in the *"Guidelines"* were consistently referred to, such as age, gender, physical health, and walking speed. Furthermore, the distribution of walking speed in the interval between the maximum and minimum values follows a normal random distribution (Wang et al., 2020).

For the physiological characteristics of passengers such as shoulder width, a normal distribution with a mean value of 43.2 cm, variance of 0.84, minimum value of 42.7 cm and maximum value of 47.3 cm was set for male shoulder width and a normal distribution with a mean value of 39.6 cm, variance of 0.94, minimum value of 39.1 cm and maximum value of 44.4 cm for female shoulder width, according to Fruin's (1971) definition.

Currently, most of the literature on the effects of ship inclination on evacuation has focused on studying the reduction degree of an individual's walking speed (Kang et al., 2019). Due to limitation of experimental safety issue and funding cost, it is not possible to observe the individual's walking speed in a heeling condition in a detailed way, and only the speed reduction factor ($\sigma$) is available as an index to represent the influence of different angles of heel. In addition, compared to land-based evacuation, the ships' layout is more compact. When evacuating from a heeling ship, a person may use walking aids, such as corridor handrails to maintain balance. Extensive literature analysis found few studies in the field can only estimate the assistance of handrails to individual's walking speed. Especially when the heeling angle is large, it is difficult to conduct comparative experiments to quantify the effect of walking aids on speed. Therefore, the reduction factor of individual's walking speed proposed in these studies already concerns the influence of handrails on individual's walk speed during the calculation process (Fang et al., 2022a).

Considering the different influence of individual's walking direction change on walking speed, the individual's walking schematic diagram of three typical scenarios is drawn as shown in Fig. 4. When the angle between the individual's walking direction and the heeling direction is 90°, the individual can be regarded as affected by heeling. However, when the included angle is 0° and 180°, it means that the individual goes downhill and uphill along the heeling angle direction respectively, which can describe the influence of trimming on walking speed. In this study, according to the angle between the individual's walking direction and the heeling direction, the detailed reduction factor ($\sigma_d$) is calculated for different levels of heeling angles using Eq. (15) based on the source provided by Fang et al. (2022a). In the simulation process, the detailed reduction factor is the average of the speed reduction factors in three scenarios where the angle between the walking direction and the heeling direction are set as 0°($\sigma_0$), 90°($\sigma_{90}$), and 180°($\sigma_{180}$), respectively. This can minimize the error of speed reduction factor caused by the individual's walking direction. The detailed reduction factors corresponding to different levels of heeling angles are shown in Table 5. The

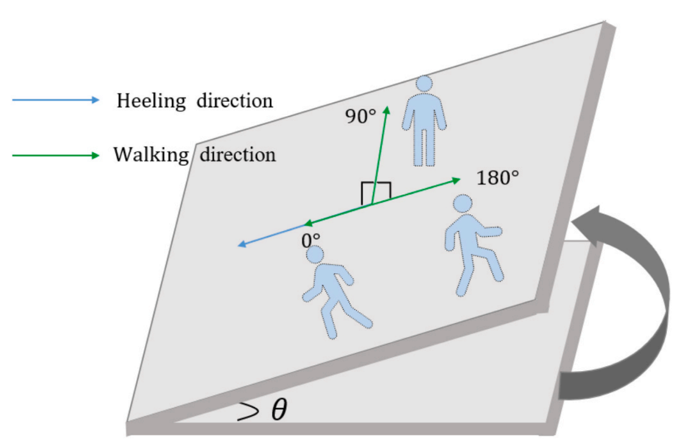


**Fig. 4.** Schematic diagram of the angle between the individual's walking direction and heeling direction.

**Table 5**
Speed reduction factor at different angles of heel.

| Angle of heel | 0° | 5° | 15° | 25° |
|---|---|---|---|---|
| $\sigma_d$ | 1 | 0.98 | 0.86 | 0.39 |

combined walking speed in the heeling scenario ($v_{heeling}$) is calculated by Eq. (16), and input into the Pathfinder, which is the product value of the detailed reduction factor ($\sigma_d$) and the normal walking speed on flat terrain ($v_{normal}$).

$$\sigma_d = \frac{\sigma_0 + \sigma_{90} + \sigma_{180}}{3} \tag{15}$$

$$v_{heeling} = \sigma_d \times v_{normal} \tag{16}$$

### 3.3. Model validation

#### 3.3.1. Simulation results of benchmark scenario

Due to the randomness of Pathfinder and population composition parameters, multiple tests of each scenario were carried out to eliminate random errors. Fig. 5 shows the results of 50 tests in the benchmark scenario. In this scenario, the response duration was set to the logarithmic normal distributions from 400 s to 700 s, which was obtained by referring to the *"Guidelines"*, the angle of heel was set to 0°, all stairs were available, there was no difference in personnel priorities and the rest of parameters were set as described in Section 3.2.

The average TET for 50 tests is 834.27 s. The variation curves of the number of passengers waiting to evacuate in 50 tests are illustrated in Fig. 5, which clearly shows that the trend was almost identical for each test. Furthermore, the pedestrians all started to take action after 400 s, which proved that the response time of passengers was greater than 400 s. For a more detailed observation of the response times, a box plot of the distribution of response times per passenger over the 50 tests is shown in Fig. 6. It was found the majority of pedestrians had response time in the range of 402–406 s. Although in some tests there were cases in which pedestrians had shown longer and shorter response time, all met the requirements in the *"Guidelines"*.

#### 3.3.2. Comparison between simulation results and real experiments

As the most intuitive index used to assess evacuation performance, TET can be used as a valid criterion to verify the reliability of a simulation. However, TET can only be used to compare simulation and experimental results from a macro perspective, and could not describe the evacuation process in detail. To further verify the applicability of the simulation software, the SGVDS2 dataset publicly released by the SAFEGUARD project was used as a supplementary verification of the

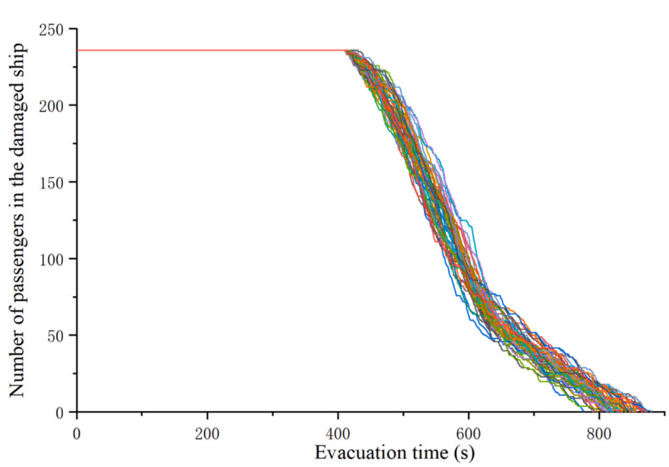


**Fig. 5.** The results of 50 tests for benchmark.

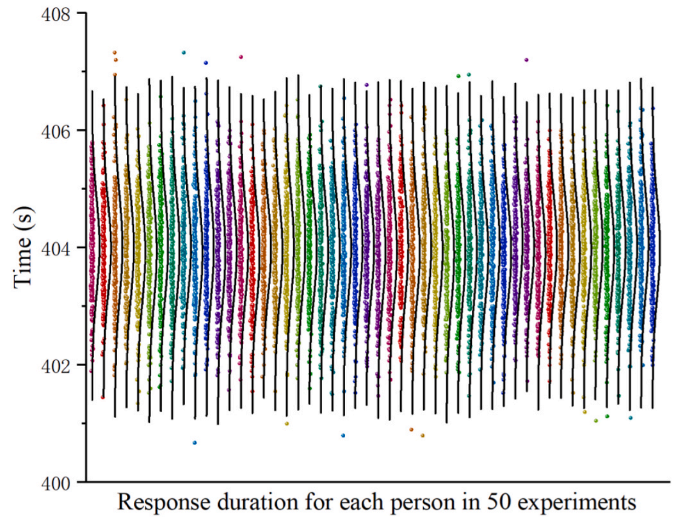


**Fig. 6.** The distribution of response durations for 50 tests.

simulation tool for evacuation on board (Brown et al., 2013; Galea et al., 2012). This dataset was collected from an experiment conducted on a cruise ship named "Jewel of the Sea". It is the most complete available actual experimental data on human evacuation from ships, including 1743 valid human data and arrival curves of four assembly stations. In addition, in order to compare the performance of commercial evacuation software, Pathfinder and Anylogic were used to conduct simulations based on the ship layout, distribution of population, and response time in the SGVDS2 dataset, respectively. Compared with the experimental data, the human arrival curves are shown in Fig. 7. It can be clearly seen from Fig. 7 that after 1000 evacuees arrive at the assembly station, the changing trend of Anylogic's arrival curve is obviously inconsistent with the experimental data, while Pathfinder is consistent with the changing trend of experimental results with smaller error.

In addition to the public verification dataset, SAFEGUARD project also provided the validation metric and acceptance criteria for the simulation of evacuation on board. It is not sufficient to evaluate the consistency of the arrival curves of the simulation and experimental results only by visual observation. Therefore, to further quantify the difference between the simulation and experimental results, four evaluation parameters, Euclidean Relative Difference (ERD), Euclidean Projection Coefficient (EPC), Secant Cosine (SC), and percentage dif-

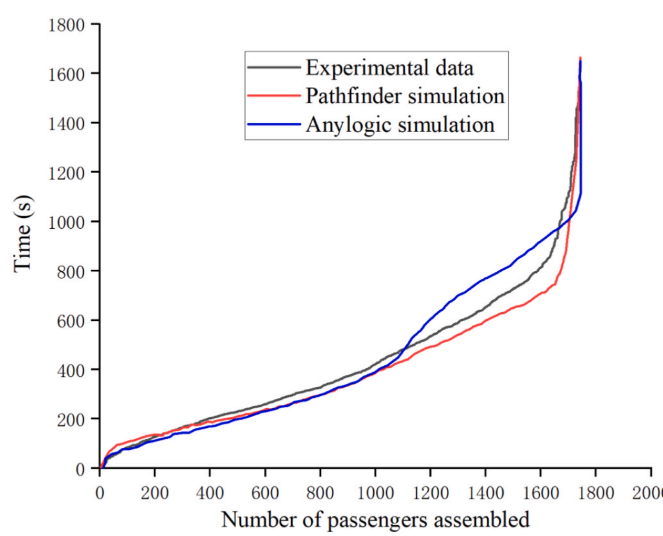


**Fig. 7.** Comparison of Pathfinder, Anylogic and SGVDS2 arrival curves (overall).

ference (%TAT), provided by the SAFGUARD project, were used to evaluate the degree of difference between the simulation and experimental data. Where, ERD is used to evaluate the difference distance between the experimental data and the simulation data, when ERD = 0, it means that the simulation results are exactly the same as the experimental data; EPC indicates the degree of agreement between the experimental data and the simulation results, when EPC tends to 1, it means that the difference between the two groups of data is small; SC is used to evaluate the similarity of the arrival curves during the experiment and simulation, when SC tends to 1, it means that the two curve shape is identical; %TAT is a measure of the difference in total evacuation time. The formulae for these evaluation parameters are shown in Eq. (17)- (20).

$$\mathrm{ERD}=\frac{\sqrt{\sum_{i=1}^{n_p}(E_i-S_i)^2}}{\sqrt{\sum_{i=1}^{n_p}E_i^2}} \tag{17}$$

$$\mathrm{EPC}=\frac{\sum_{i=1}^{n_p}E_iS_i}{\sum_{i=1}^{n_p}E_i^2} \tag{18}$$

$$\mathrm{SC}=\frac{\sum_{i=s+1}^{n_p}\frac{(E_i-E_{i-s})(S_i-S_{i-s})}{s^2(t_i-t_{i-1})}}{\sqrt{\sum_{i=s+1}^{n_p}\frac{(E_i-E_{i-s})^2}{s^2(t_i-t_{i-1})}\sum_{i=s+1}^{n_p}\frac{(S_i-S_{i-s})^2}{s^2(t_i-t_{i-1})}}} \tag{19}$$

$$\%\mathrm{TAT}=\frac{|E_{TET}-S_{TET}|}{E_{TET}}\times 100\% \tag{20}$$

where, $E_i$ denotes the $i$th data point in the experimental dataset and $S_i$ is the $i$th data point in the simulation dataset; np represents the total number of data points; $s$ is a "smoothing" term, which is used to remove noise points from the dataset and its value is determined according to the $n_p$, $t$ is the evacuation time corresponding to the data point; $E_{TET}$ and $S_{TET}$ are the total evacuation times for the experiment and simulation, respectively. The SAFEGUARD project considered that the simulation of the evacuation on board should meet the acceptance criteria for each evaluation parameter, i.e. ERD≤0.25, 0.8≤EPC≤1.2, SC ≥ 0.8 (when $s/n_p = 0.03$) and %TAT≤15%.

In order to compare the experimental results with the simulation results in a more detail manner, the arrival curves of four assembly stations (AS-A, AS-B, AS-C, AS-D) in the experiment and simulation are plotted in Fig. 8. Moreover, the four discrepancy evaluation parameters were calculated respectively, as shown in Table 6. It can be seen that the results obtained from the simulation meet the acceptance criteria for all evaluation parameters, and that the arrival curves from the simulation match the experiment well. Therefore, Pathfinder is able to meet the requirements for human evacuation from ships and its simulation results are very close to the actual situation.

## 4. Results and discussion

### 4.1. Orthogonal experiment results

The influential factors affecting human evacuation from heeled ships and the indices for the evaluation of the evacuation results were

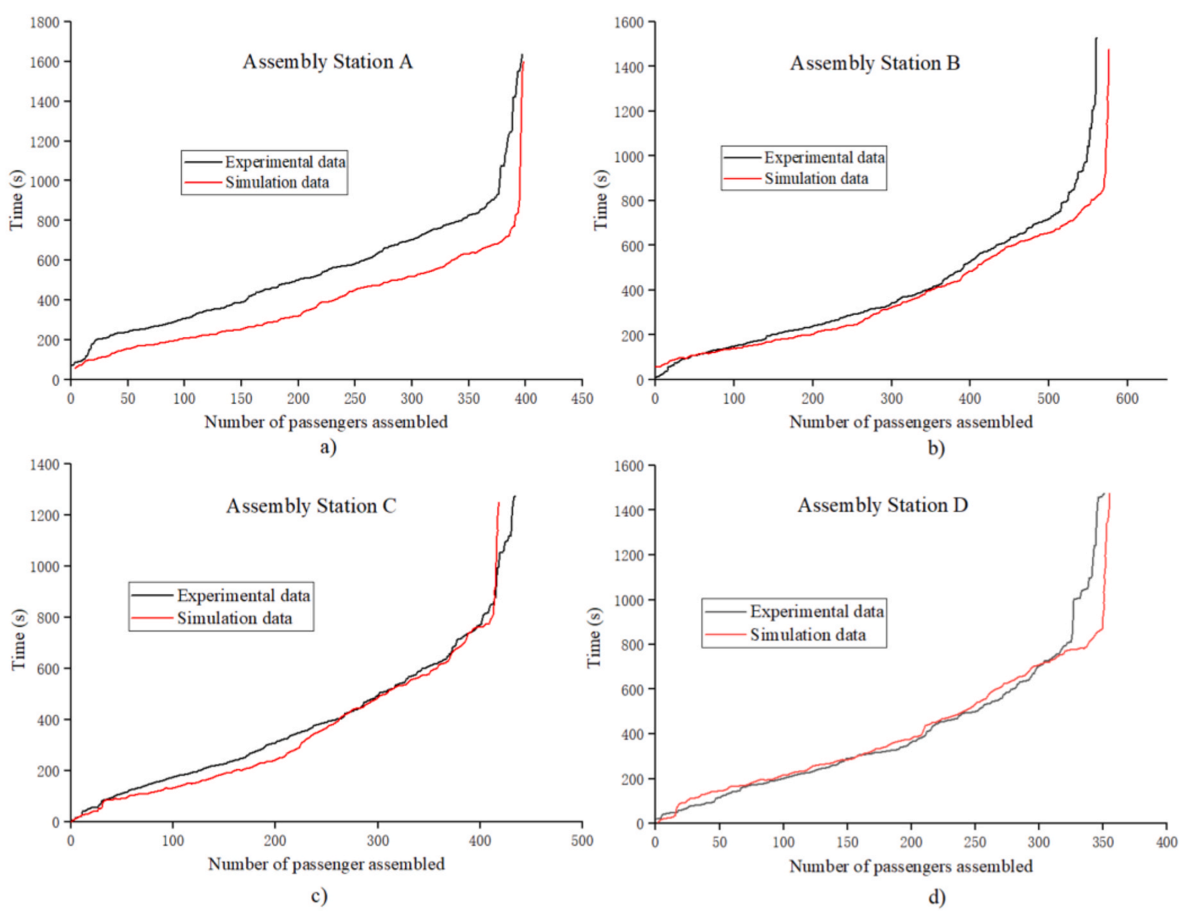


**Fig. 8.** Comparison of arrival curves of four assembly stations.

**Table 6**
Simulation results and calculated values of each evaluation parameters.

| Area | Evacuation time (s) | | ERD | EPC | %TAT | $s/n_p$ | SC |
|---|---|---|---|---|---|---|---|
| | Simulation | Experiment | | | | | |
| Overall | 1609 | 1637 | 0.162 | 0.900 | 1.71% | 0.03 | 0.85 |
| AS-A | 1609 | 1637 | 0.152 | 0.876 | 1.71% | 0.03 | 0.83 |
| AS-B | 1498 | 1528 | 0.165 | 0.913 | 1.96% | 0.03 | 0.91 |
| AS-C | 1250 | 1274 | 0.173 | 0.826 | 1.88% | 0.03 | 0.89 |
| AS-D | 1440 | 1473 | 0.098 | 0.965 | 2.24% | 0.03 | 0.81 |

carefully introduced in Section 2, so that an orthogonal experiment is designed as $L_{16}$ ($4^5$) based on three factors and four levels (Moore et al., 2006). The minimum orthogonal table and the results of simulations under different levels are shown in Table 7. These results are the average of 50 simulations, which can eliminate random errors and outliers, ensuring that the most appropriate and representative. Meanwhile, based on the standard orthogonal experimental table and multiple simulation results, it can effectively ensure the accuracy of subsequent sensitivity analysis of indices.

Considering that the simulations of human evacuation from heeled ships involved multiple influential factors and evaluation indices, in order to analyse the influence of the influential factors on evaluation indices, the range analysis and the ANOVA are used to analyse the research results which are presented in detail in Sections 4.2 and 4.3, respectively.

### 4.2. Range analysis

#### 4.2.1. Influence of factors on the TET

The influence curves of the three influential factors on TET are shown in Fig. 9. It can be seen from Fig. 9 that the maximum effect value of the heeling angle on TET is obtained at level 4, while the minimum value is obtained at level 1. To demonstrate the range analysis more visually, the R-values of different influential factors on each evaluation index are illustrated in Fig. 10, in which the heeling angle has an R-value of 594.28 on TET. The variation of the number of un-evacuated passengers in 16 evacuation simulations is shown in Fig. 11. It is evident that with the increases of heeling angle, the evacuation time increases obviously, especially when the heeling angle reaches 25° (level 4, tests 13–16), the TET increases sharply. For the heeling angle of 15° (level 3), the TET increases by 71.7 s compared to flat terrain (level 1), which is far less than that at 25°, although the individual's walking speed decreases by 15% at level 3. This result is consistent with the findings of literature that the evacuation deteriorates sharply when the heeling angle reaches 25°. Even though the details studied in the literature are inclined scenarios in which people escape from a room (local area), its conclusions are still applicable to the full-size evacuation in this study.

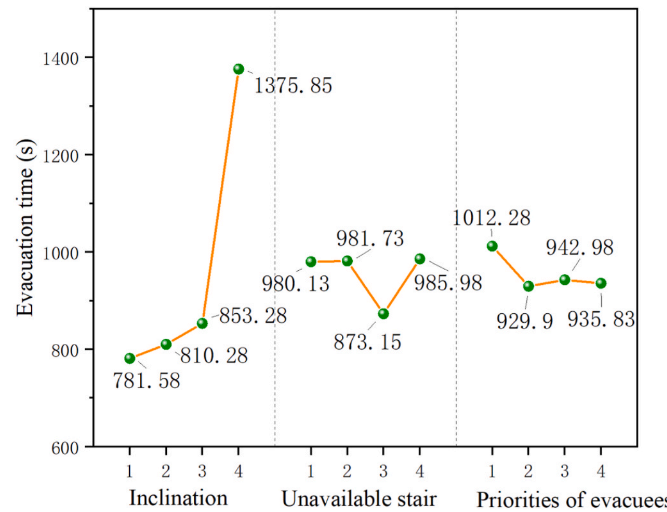


**Fig. 9.** The evacuation time for different factors at different levels.

It is illustrated that the full-size evacuation simulation remains consistent with the findings of the Fang et al. (2022a) regarding the effect of different angles of heel on evacuation time in limited areas, *i.e.* while at an angle of heel of 15°, there is some attenuation of pedestrian speed, but the evacuation time does not increase sharply, whereas when the heeling angle reaches 25°, the evacuation time increases exponentially.

It is found that unavailable stairs at different decks also affected the TET. As observed in Fig. 11, the evacuation efficiency is the greatest when the unavailable stair is located on the main deck (level 3) and the least on the tween deck (level 4), and the R-value is 112.83 in Fig. 10. It is worth noting that the main deck contains the largest number of stairs

**Table 7**
The results of orthogonal experiments.

| No. | Factors | | | | Indices | | |
|---|---|---|---|---|---|---|---|
| | Angle of heel | Unavailable stair | Priorities of evacuees | Error | TET (s) | MCT (s) | OPSS |
| 1 | 1 | 1 | 1 | 1 | 838.0 | 96.82 | 1.976 |
| 2 | 1 | 2 | 2 | 2 | 807.0 | 95.39 | 2.021 |
| 3 | 1 | 3 | 3 | 3 | 717.8 | 46.13 | 1.239 |
| 4 | 1 | 4 | 4 | 4 | 763.5 | 57.08 | 1.450 |
| 5 | 2 | 1 | 2 | 3 | 829.5 | 112.22 | 2.029 |
| 6 | 2 | 2 | 1 | 4 | 875.3 | 112.79 | 2.044 |
| 7 | 2 | 3 | 4 | 1 | 746.5 | 55.24 | 1.257 |
| 8 | 2 | 4 | 3 | 2 | 789.8 | 62.54 | 1.370 |
| 9 | 3 | 1 | 3 | 4 | 877.5 | 138.39 | 2.160 |
| 10 | 3 | 2 | 4 | 3 | 857.8 | 126.17 | 2.059 |
| 11 | 3 | 3 | 1 | 2 | 811.5 | 73.57 | 1.423 |
| 12 | 3 | 4 | 2 | 1 | 866.3 | 82.35 | 1.448 |
| 13 | 4 | 1 | 4 | 2 | 1375.5 | 519.00 | 2.133 |
| 14 | 4 | 2 | 3 | 1 | 1386.8 | 521.07 | 2.126 |
| 15 | 4 | 3 | 2 | 4 | 1216.8 | 403.59 | 1.357 |
| 16 | 4 | 4 | 1 | 3 | 1524.3 | 408.48 | 1.688 |

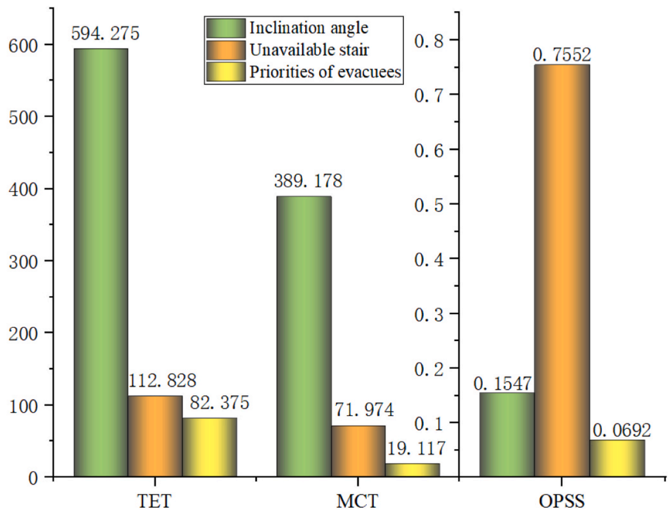


**Fig. 10.** R-value of three influential factors for the various indices.

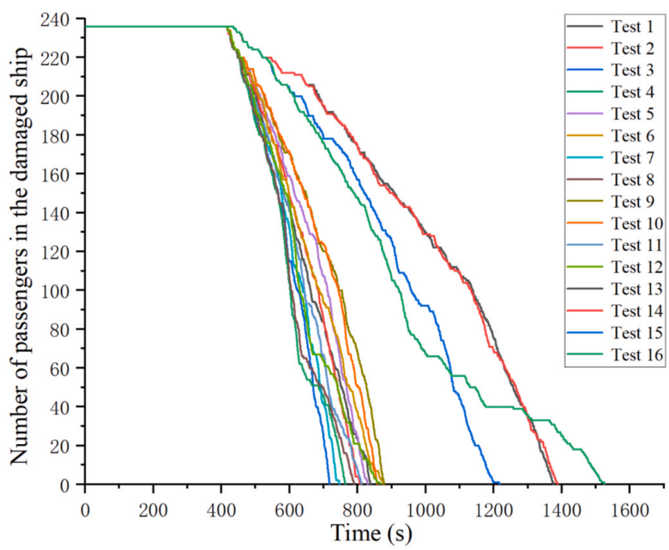


**Fig. 11.** The changes in the number of people not evacuated over time in 16 tests.

compared to other decks. Therefore, even if the main deck contains the most cabins and passengers, the influence on evacuation results is still minimal when the stair with the greatest capacity on the main deck is not available. Furthermore, the direct effect of the number of stairs on the TET can be illustrated by this set of tests, and it is critical to consider the number of available stairs when there are unusable stairs.

Intriguingly, the impact of different levels of priorities of evacuees on the TET is irregular, which is different from the other two factors. Fig. 9 shows that the evacuation time is the shortest when the number of priorities of evacuees is level 2. However, as the number of priorities increases, the evacuation time does not change significantly, the TET is the highest when all passengers with the same priority (level 1), reaching 1012.28 s. Therefore, the optimal priorities of evacuees should be divided into 2 levels, which can generate some competitive behaviours, *i.e.* evacuees with impaired mobility should be given priority in the competition for the target point. Kang et al. found that a small amount of competitive behaviours can accelerate evacuation dynamics during evacuation on heeled ships, which is consistent with this result (Kang et al., 2019).

### *4.2.2. Influence of factors on the MCT*

The distribution of the congestion time for each passenger over the 16 tests is given in Fig. 12. The MCT for each test is connected by the red line, which can be found haphazard and irregular due to the fact that the variables of all factors in these 16 tests were set heterogeneously. For a more visual analysis of the effect of those three factors, the MCT at different levels of factors is demonstrated in Fig. 13. It can be seen that there are similar effects of the heeling angle on the MCT and TET, and the R-value of the heeling angle on the MCT is 389.178, as shown in Fig. 10. The MCT increases slowly as the heeling angle increases when the heeling angle is less than 25°, but when the angle of heel reaches 25°, the MCT increases sharply and is more than tripling compared to the heeling angle of 15°. It is confirmed that heeling may reduce the evacuation efficiency and especially aggravate congestion when the heeling angle exceeds 25°.

For the unavailable stair considered in these tests, the R-value on the MCT is 71.974, as shown in Fig. 10. Fig. 13 shows that the minimal MCT is 144.636 s when the unavailable stair is set on the main deck, and the closer the unavailable stair to the assembly deck, the longer the congestion time. The main reason for this phenomenon is still similar to that analysed above, the main deck has a sufficient number of stairs, which can reduce the pedestrian density more quickly in congested areas, leading to the MCT being minimal in this scenario. Also, Ren et al. (2021) revealed that maintaining a balanced distribution of pedestrian density on each area is essential and thus the evacuation efficiency can be improved.

Compared to the heeling angle and unavailable stair, the effect of the priorities of evacuees on the MCT is not significant, with an R-value of only 19.117 in Fig. 10. Although the longest evacuation time is found when priorities are not differentiated in the analysis of the TET, the opposite impact is obtained in its effect on the MCT. When priorities are more differentiated, the MCT increases, however, when there is only one priority for all passengers (level 1), the MCT is minimal compared to the other classifications of the priorities of evacuees. The reason for this could be that in levels 2, 3, 4, elderly pedestrians with impaired mobility have the priority in passing, and their lower speed causes the movement of the pedestrians behind them to be affected, thus increasing the MCT.

### *4.2.3. Influence of factors on the OPSS*

It is found that when the heeling angle changes from level 1 to 4, the value of the index OPSS tends to increase, and the R-value is 0.1547 in Fig. 10. When the heeling angle reaches 15°, the OPSS value starts to increase rapidly in Fig. 14. When the heeling angle is at 25°, the OPSS

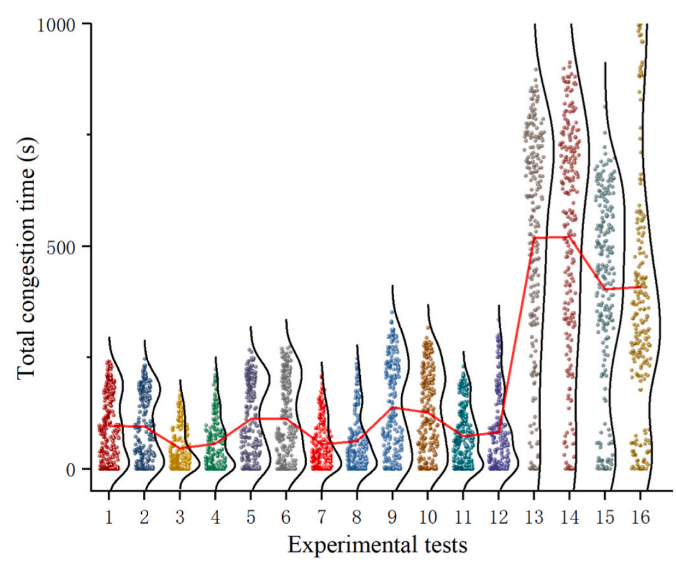


**Fig. 12.** The distribution of total congestion time for each passenger in 16 tests.

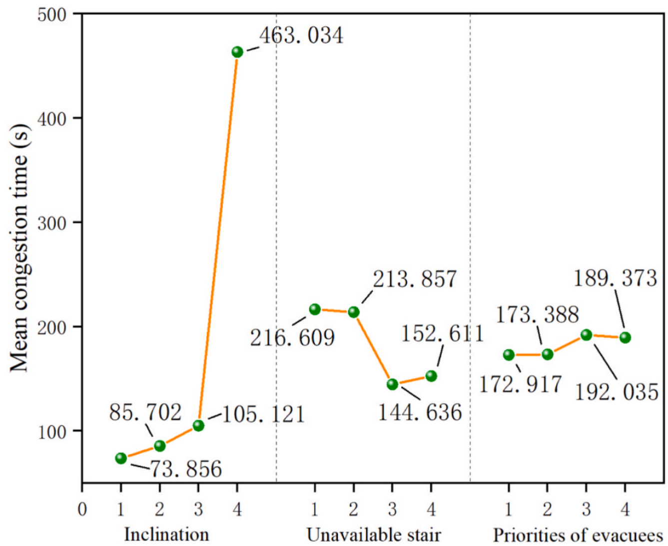


**Fig. 13.** The MCT for different factors at different levels.

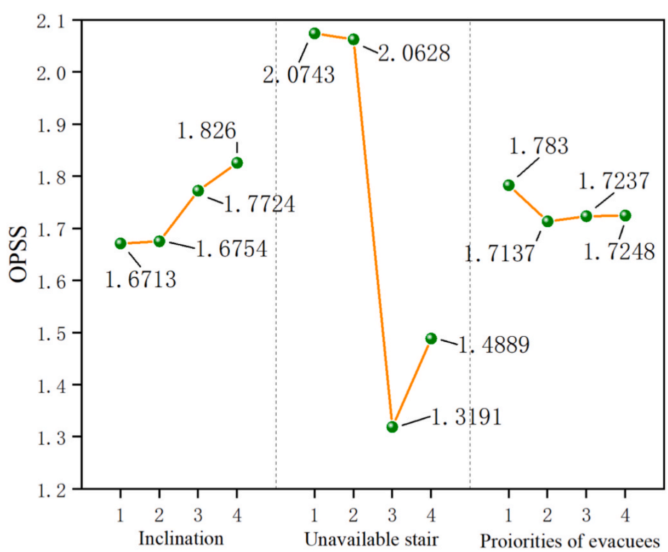


**Fig. 14.** The OPSS for different factors at different levels.

has the maximum value 1.826, *i.e.* the lowest utilization of stairs. It is mainly because the larger angle of heel causes each stair to be used for a longer duration, and the OPSS value is the sum of the usage ratios of multiple stairs on all decks, resulting in the OPSS being amplified by the longer usage duration of stairs. The OPSS value thus increases as the heeling angle increases.

Unlike the effect on the indices TET and MCT, the unavailable stair has the greatest effect on the OPSS value with an R-value of 0.7552 in Fig. 10. Since OPSS is used to evaluate the efficiency of stairs' usage, the OPSS value is directly affected by the unavailable stair, and has the minimal value at level 2 (unavailable stair on the main deck). There are four stairs located on the main deck and when the stair with the highest capacity is unavailable, evacuees are allocated to other stairs so that the difference in usage duration of each stair on the same deck becomes smaller, resulting in an optimal OPSS value. In addition, when an unavailable stair is located on the boat deck or promenade deck, the OPSS value becomes larger which means the stairs are less utilised. This phenomenon is due to the fact that there are only two stairs on boat and promenade decks, and when one of them is unavailable, pedestrians need to use the other stair, which causes the individual OPSS values on the deck to reach an upper limit of 1, resulting in a larger total OPSS value. Lei and Tai (2019) focused on the influence of stairs and exits on evacuation, and discovered that the number of stairs had the greatest impact on evacuation results compared to the location and size of the stairs. Therefore, it is believed that evacuation is the most efficient when a reasonable number of stairs are installed, which can verify the validity of the current analysis.

The effect of priorities of evacuees on OPSS is similar to that of TET, with an R-value of 0.0692, which achieves its minimum value at level 2. It is indicated that the stair usage is optimal when there are only two priority levels for all pedestrians. The observation of the 3D evacuation process shows that pedestrians with impaired mobility are prioritised for evacuation during the escape process, while other pedestrians with faster walking speed may choose the distant stairs, which leads to a more balanced usage efficiency between the stairs and a satisfactory OPSS value. More often, when pedestrians are assigned with too much priority, there is a more competitive behaviour between pedestrians when using stairs, which can also be detrimental to the evacuation process, and cause the unbalanced stairs' usage.

Based on the range analysis of each experimental index, it can be revealed that the heeling angle had the largest influence on two indices (TET and MCT), while unavailable stairs had the most significant effect on OPSS. However, the priorities of evacuees were not considered to be the most important influential factors in any index, and its different levels only caused a small magnitude of change on each of those indices. Combining these factors on the three indices in the range analysis, the effects of the factors on the experimental indices are ranked from the largest to smallest as: heeling angle > unavailable stair > priorities of evacuees.

### *4.3. ANOVA*

ANOVA as a standard statistical method can estimate the relative significance of each parameter in the overall response, and the results can present the magnitude of the effect of each factor on indices in precise values. The ANOVA for the TET is shown in Table 8, which contains the sum of squares (*SS*), degrees of freedom (*f*), mean square (*MS*), variance ratio *F*, and critical value $F_\alpha$. It is found that the heeling angle has a very significant effect on the TET by comparing the F-values with the $F_\alpha$. Meanwhile, the presence of unavailable stairs at different decks also has an influence on the TET. However, the F-value corresponding to the priorities of evacuees is lower and its effect on the TET is not statistically significant.

Similarly, the ANOVAs for the MCT and OPSS are shown in Table 9 and Table 10. It is notable that in Tables 9 and 10, since the *MS* of priorities of evacuees is less than twice the *MS* of error (*e*), the deviation squared and degree of freedom of this factor should be incorporated in the error to increase the *MS* and *f* of the error and improve the sensitivity of the F-value inspection. In Tables 9 and it can be observed that the heeling angle still has a high F-value, which indicates this factor also has a very significant effect on the MCT. The F-value of the unavailable stair is greater than $F_{0.05}$ (3, 6), and its change has a significant influence on the MCT. However, in Tables 10 and it is found that the unavailable stair, as a parameter that directly affects the efficiency of stairs' usage, has a very significant effect on the OPSS values. The F-value for the

**Table 8**
ANOVA for the TET.

| Sources | *SS* | *f* | *MS* | *F* | Significance |
|---|---|---|---|---|---|
| Heeling angle | 953936.1 | 3 | 317978.7 | 180.53 | *** |
| Unavailable stair | 36016.5 | 3 | 12005.5 | 6.82 | * |
| Priorities of evacuees | 17689.9 | 3 | 5896.6 | 3.35 | |
| *e* | 5284.1 | 3 | 1761.4 | / | |
| $F_\alpha$ | $F_{0.1}$ (3, 3) = 5.39 $F_{0.05}$ (3, 3) = 9.28 $F_{0.01}$ (3, 3) = 29.46 | | | | |

*** very significant influence, ** significant influence, * certain influence.

**Table 9**
ANOVA for the MCT.

| Sources | *SS* | *f* | *MS* | *F* | Significance |
|---|---|---|---|---|---|
| Heeling angle | 423435.9 | 3 | 141145.3 | 438.02 | *** |
| Unavailable stair | 17889.7 | 3 | 5963.2 | 18.51 | ** |
| Priorities of evacuees | 1246.8 | 3 | 415.6 | / | |
| $e$ | 686.6 | 3 | 228.9 | / | |
| $e^{\Delta}$ | 1933.4 | 6 | 322.2 | | |
| $F_{\alpha}$ | $F_{0.1}$ (3, 6) = 3.29 $F_{0.05}$ (3, 6) = 4.76 $F_{0.01}$ (3, 6) = 9.78 | | | | |

*** very significant influence, ** significant influence, * certain influence.

**Table 10**
ANOVA for the OPSS.

| Sources | *SS* | *f* | *MS* | *F* | Significance |
|---|---|---|---|---|---|
| Heeling angle | 0.06915 | 3 | 0.02305 | 7.30 | ** |
| Unavailable stair | 1.82405 | 3 | 0.60802 | 192.43 | *** |
| Priorities of evacuees | 0.01189 | 3 | 0.00396 | / | |
| $e$ | 0.00701 | 3 | 0.00236 | / | |
| $e^{\Delta}$ | 0.01896 | 6 | 0.00316 | / | |
| $F_{\alpha}$ | $F_{0.1}$ (3, 6) = 3.29 $F_{0.05}$ (3, 6) = 4.76 $F_{0.01}$ (3, 6) = 9.78 | | | | |

*** very significant influence, ** significant influence, * certain influence.

heeling angle in Table 10 is greater than the critical value of the test level $\alpha = 0.05$, indicating that its variation also has a significant effect on OPSS.

In summary, it is clear from a comprehensive comparison that the factors affecting the evacuation effect in descending order of heeling angle > unavailable stair > priorities of evacuees, which is the same as the results of the range analysis and validates the previous calculations.

### 4.4. Discussion

Based on the findings of this study, it is suggested that in an emergency, the managers should organise evacuation as soon as possible to avoid the ship listed excessively and making evacuation more difficult. For example, in the "Sewol" accident, captain's delay in issuing evacuation instruction caused the ship's list to worsen, resulting in 304 deaths as the passengers missed the best time window to escape (Lee, 2015). Therefore, it can be evident that it is crucial to capture the impact of different heeling angles on all pedestrian movements from a system perspective, which can provide safer and more scientific recommendations to managers when developing evacuation strategies for specific scenarios (Fang et al., 2022a; Sun et al., 2018a).

The stairs as a key factor in the evacuation process, some meaningful results are obtained by setting up different locations of unavailable stairs. It is a reminder that measures should be taken to ensure that enough stairs be available during an emergency evacuation (Wang et al., 2022a). Especially for ships with fewer stairs, the evacuation can be more negatively affected if there are not sufficient stairs available. In other words, the larger the percentage of stairs that are not available from an overall perspective, the more difficult it becomes to escape, which means more danger for the passengers (Psyroukis, 2022).

In fact, passengers are the main subject during the evacuation, and the competing desires presented by themselves have a certain impact on the evacuation results. Many studies have shown that severe congestion leads to a confusing escape process, which hinders the fluidity of the passing flow, and the absence of competition among all passengers also failed to optimize evacuation results. Meanwhile, the findings of this study are consistent with previous studies through the tests regarding the classification of the priorities of evacuees (Cao et al., 2021; Wang et al., 2015). Therefore, it is recommended that crews give priority to pedestrians with impaired mobility when organising evacuation during an evacuation based on numerical analysis.

## 5. Conclusion

Ship layout and passengers' behaviour jointly have a significant impact on evacuation results and evacuation efficiency, but there are still gaps in current research and a lack of valid data on human evacuation from passenger ships. To investigate the complex evacuation process on heeled ships, an orthogonal test with multiple factors and levels was proposed to evaluate the overall evacuation results and efficiencies. This method exploits the balanced nature of orthogonal experiments and allows the effects of multiple factors on evacuation results to be analysed using only a series of representative tests. Some unique factors (heeling angle, unavailable stair, priorities of evacuees) and indices (TET, MCT and OPSS) were set to assess the final results and details of evacuation process. The simulation tests were then carried out using the proposed methodology with the MV *"Yukun"* as a case study. Finally, scientific analysis methods were applied to obtain meaningful results and practical implications.

Analysis of the data from 16 tests shows that the heeling angle has significant effects on TET, MCT and OPSS, which means that the heeling angle not only extends evacuation time but also reduces evacuation efficiency. All three indices increase as the inclination becomes more severe, especially these indices achieve their maximum value when the heeling angle reaches 25°. It is indicated that the evacuation effect is worst in the scenario with a large angle of heel. Secondly, by comparing a series of tests, it is observed that there is a significant difference in the evacuation results when the unavailable stair is located on different decks. In the case study, the evacuation result is optimal when the unavailable stair is located on the main deck; TET, MCT and OPSS are reaching a minimal value. It is primarily due to the fact that there are three stairs on the main deck, even if an unavailable stair is located on this deck, the other stairs still enable pedestrians to complete the evacuation quickly. Furthermore, the priorities of evacuees are an influencing factor considered from the standpoint of passengers' behaviour, and its effect on the three indices is less significant than the other two factors, but it still varies at different levels. It is revealed that indices TET and OPSS showed almost identical trends at different levels of priorities of evacuees based on analysis of the results, with both reaching an optimum at level 2. Although the index MCT is optimal at level 1, it also increases by only 0.27% at level 2. Therefore, on a combined assessment, the evacuation is best when the priorities of evacuees are divided into 2 levels.

The results and conclusions provide effective guidance for the development of evacuation strategies on heeled ships. Using the proposed experimental methods and evaluation indexes, more complex experiments can be carried out in the future to analyse more factors to further improve the safety level of passenger ship transportation. In addition, this innovative method can more intuitively show the effects of various influential factors on evacuation results, to identify some key factors effecting the human evacuation process from ships. While the IMO encouraged the member states to update the "*Guidelines*" by conducting research on human evacuation from ships in different scenarios, the framework proposed by this work, addressing the need, can provide theoretical support for the updating of "*Guidelines*". However, this study has some limitations, such as insufficient quantification of the influence of handrails on walking speed, which will be further studied in future experiments.

## CRediT authorship contribution statement

**Siming Fang:** Conceptualization, Methodology, Validation, Writing – original draft, Investigation. **Zhengjiang Liu:** Conceptualization, Validation, Project administration, Supervision. **Xihan Yang:** Validation, Writing – original draft, Formal analysis, Resources. **Xinjian Wang:** Conceptualization, Formal analysis, Funding acquisition, Resources. **Jin Wang:** Supervision, Validation, Writing – review & editing. **Zaili Yang:** Formal analysis, Validation, Writing – review & editing, Supervision.

## Declaration of competing interest

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

## Data availability

The authors do not have permission to share data.

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