Abstract
Lifeboats are important equipment to ensure the safety of passengers when a serious accident occurs in the ship. Higher efficiency of lifeboat embarkation is beneficial to improving passenger survival. This study divides lifeboat embarkation into queuing and seat selection stages and studies the embarkation process of cruise passengers. According to the characteristics of two stages of the embarkation process, transfer rules of queue and activity rules of the passenger are proposed. Combined with the rules, 16 types of embarkation simulation scenarios are established. The simulation results show that the embarkation efficiency of the group passenger is lower than that of the individual passenger. When passengers select seats from outboard row to inboard row, the speed of embarkation is faster than that of random seating selection. Compared with only considering the queue length, the embarkation is more efficient if passengers also consider the seat availability of lifeboats when they transfer between queues. The analysis of the results proves that the embarkation efficiency can be improved through proper guidance on the behavior of passengers in queuing and seat selection.

1. Introduction
Maritime lifesaving is one of the important concerns for the operation of the cruise ship. If the ship cannot maintain its normal condition in case of a serious accident occurs, passengers need to abandon the ship through lifeboats. The embarkation station is usually located on one deck of the cruise ship, and all passengers need to embark on the lifeboat from the station. However, passenger panic will have a negative impact on the embarkation process in an emergency. Compared with ordinary passenger ships, cruise ships carry a large number of passengers. In order to ensure passenger safety, the highly effective organization of the embarkation process is essential.

For the safety of the ship passengers, some scholars have conducted research on the maritime lifesaving system. The lifesaving system of the ship is an integral part of emergency equipment in the process of abandoning the ship [1]. Divkovic and Dahlrot [2] introduced requirements in the process of lifeboat embarkation and launching based on IMO’s (International Maritime Organization) International Life-Saving Appliance (LSA) Code [3]. They recruited 25 volunteers to participate in the lifeboat embarkation experiment and carried out the experiment for the lifeboat embarkation process of the cargo ship. It took three minutes and 52 seconds for all volunteers to embark on the lifeboat, which is 52 seconds longer than the three minutes required by LSA Code.

The safety, reliability, and other factors of lifeboat systems are very important to the safety of passengers. Abramowicz-Gerigk and Burciu [4] took the evacuation of offshore platforms as the research object, and they introduced the general evaluation method for marine lifesaving systems and selected liferafts as an example to conduct safety evaluation. In addition, the lifeboat system will also impact by other factors such as the matching degree between the
lifeboat capacity and the number of assembled passengers [5], the human error in the operation of the lifeboat system [6], and the evacuation behavior of passengers [7]. Conversely, the process of embarkation and launching the lifeboat will also have a negative impact on the health of passengers [8]. The positions of objects or persons in the space could be collected by using wireless sensors or Internet of things devices [9–12]. Based on the existing lifeboat system, Andreadakis et al. [13] explored the possibility of establishing a wireless system for detecting the safety of passengers. Passengers wear bracelets with near-field communication or radio-frequency identification, and bracelets would record the relevant data through card readers when passengers embarked on lifeboats. Then, the system could allow the crew to obtain accurate evacuation statistics in real time.

When passengers arrive at embarkation stations, they will generally queue up to embark lifeboats under the organization of staff or by self-organization. Some scholars have studied the behavior of pedestrians in the queuing process. The service efficiency of the queue is usually affected by the organization of the queue, and the customer waiting time could be reduced by reasonable redistribution and management of the queue [14]. The pedestrian flow through services is also related to the number of services and service points [15]. In addition, the width, type, and the bottleneck in the path will have an impact on the movement of the pedestrian queue. Zhang et al. [16] analyzed the relationship between the bottleneck and pedestrian queuing characteristics through experiments. Köster and Zönnchen [17] added a loosely queuing model to the pedestrian flow model to simulate the movement behavior of pedestrians at the place of evacuation bottleneck. Zhuang et al. [18, 19] proposed an agent-based cellular automaton to study the aggregation of pedestrian flow at the bottleneck and the impact of self-organizing queue behavior on pedestrian movement efficiency.

The behavior of pedestrians has an impact on the queuing process, and some evacuation models are used to simulate queuing behavior. The cellular automata model as one of the evacuation models can be used to analyze the interaction between pedestrians. This model had been used to simulate the queuing behavior of pedestrians at the server window in the canteen [20, 21] and queuing behavior of students who evacuate from the classroom [22, 23]. Wu and Guo [24] constructed a microscopic pedestrian model with the potential field that can drive the movement of pedestrians. In the model, pedestrians can intersect with others at different angles, and they explored the impact of the intersection angle between passing pedestrians and queuing pedestrians on pedestrian movement efficiency. In another study, Zheng et al. [25] proposed a new concept of the queuing line, which divides the queuing process into walking and queue selection stages. Based on the social force model and queuing theory, they developed two microsimulation models to simulate these two stages. In considering the effect of walking distance [26] and volume [27] of the pedestrian in the queuing process, Yanagisawa et al. established the pedestrian queuing system [28] combined the queuing theory with the microspatial discrete model in pedestrian dynamics. Taking service windows as objects [29], they studied the influence of pedestrian tendencies, windows locations, queue length on pedestrian transit time, and entrance blocking rate.

Family and friends often travel together on the cruise tour. They usually will spontaneously form groups, which have a relevant influence on the crowd dynamics behavior, and groups usually tend to act together [30]. Pan et al. [31] discussed the influence of small group behavior on evacuation and established a multi-agent evacuation model. By changing the type of groups and widths of passage, they simulated unidirectional and bidirectional evacuation processes. Nguyen et al. [32] built two models that contained random and logistic regression models, and they combined the controlled behavior experiment of fire evacuation to simulate the process of individual and group evacuations.

There is a correlation between the group size and the walking speed of the group. The mean walking speed of the group decreased with the increase of the group size [33], but the total evacuation time would decrease when the number of the group increased [34]. The evacuation efficiency of groups with self-organized queues at the exit was higher than that without queues [35]. In the process of group evacuation, individual members would reunite with the group after separating [36]. If the group is made up of family members, the mutual assistance between family members would have a negative impact on the evacuation process [37]. Moreover, the emotions of pedestrians will have a certain impact on evacuation efficiency. The emotions would spread between group members [38], and the propagation of emotion could improve crowds’ cognition of danger and increase the survival rate of pedestrians [39]. If the evacuation is guided by a group leader, the evacuation efficiency of the group would also be improved [40].

The embarkation process of lifeboats has its special characteristics: first, unlike ordinary queuing problems, the capacity of the lifeboat is limited, and it is also difficult for passengers outside the lifeboat to obtain internal information. Once the number of entered passengers is about to reach the capacity of the lifeboat, it has a negative effect on the embarkation efficiency if there are many passengers waiting outside the lifeboat. Second, group passengers tend to choose the same queue or enter the same lifeboat, and the embarkation process may be affected by group behavior. Finally, the space inside the lifeboat is extremely tight. The average area for each passenger is less than 0.3 m², and the space between seats is also used as the passage. If passengers who enter the earlier take seats near the door or inboard place, it will hinder the movement of subsequent passengers who would enter the lifeboat. At present, there are few studies on the embarkation efficiency of lifeboats by considering the behavior of passengers inside and outside the lifeboat. There are multiple lifeboats arranged on the cruise ship, and the rational embarkation process is particularly important for improving the efficiency of passengers.

The main contributions of this study are as follows: first, according to the embarkation characteristics of lifeboats, we divide the embarkation process into the queuing process...
Queuing theory is mostly

2.1. Queuing Model of Lifeboats.

146 persons. Lifeboat 2 is a single deck, and its capacity is double-deck lifeboats, and the capacity of these two lifeboats embarkation area on the portside. Lifeboats 1 and 3 are on each side of the embarkation deck. Figure 1 shows the research object is a medium cruise ship with three lifeboats embarkation model of the lifeboat and queue is established. The embarkation and launching of the lifeboat are the final process: the passengers preparing to enter the lifeboat to verify the number of the remaining seats left inside the lifeboat. Hence, it is not beneficial to embark as there are many passengers waiting outside the lifeboat when the capacity of the lifeboat is nearly full. If passengers are under the guidance of the staff, these passengers could transfer among queues by considering the remaining seats of lifeboats.

Once entering the lifeboat, passengers may select seats at random. However, random seating selection may hinder the entry of subsequent passengers because of the narrow interior space of lifeboats. If passengers inside the lifeboat select seats from outboard row to inboard row under the guidance of the staff, then the passenger outside the lifeboat can enter the lifeboat smoothly.

Based on the above analysis, transfer rules of passengers between queues can be divided into four types: transfer between queues of all lifeboats (TAL), transfer between queues that belong to the same lifeboat (TSL), transfer between queues that belong to the same lifeboat based on the seat availability of lifeboats (TSLSA), and transfer between queues that belong to the same lifeboat based on the seat availability of lifeboats (TSLSA). Activity rules of passenger can be divided into four types: the individual passenger selects seats from outboard row to inboard row (ISSOI), the individual

2. Description of the Research Problem

The embarkation and launching of the lifeboat are the final steps for passengers to abandon the ship. When passengers arrive at the embarkation station, they can embark on lifeboats under the guidance of the staff or by action themselves. To simulate the embarkation process, the embarkation model of the lifeboat and queue is established. The research object is a medium cruise ship with three lifeboats on each side of the embarkation deck. Figure 1 shows the embarkation area on the portside. Lifeboats 1 and 3 are double-deck lifeboats, and the capacity of these two lifeboats is 305 persons. Lifeboat 2 is a single deck, and its capacity is 146 persons.

2.1. Queuing Model of Lifeboats. Queueing theory is mostly used to model pedestrians arriving at a service facility in a certain way. When pedestrians arrive at the service point, they stand in line and wait until their turn to be served. Once passengers have received service, they are usually assumed to have left the system. Queues models are mainly divided into M/M/C and M/M/1. In M/M/C model, pedestrians are placed in one queue, and pedestrians can receive services from multiple service points. In this queuing mode, pedestrians can only move in an orderly way, and the mobility of pedestrians is limited. This model is widely used in airport check in. In M/M/1 model, multiple queues are arranged in parallel, and each queue corresponds to a service point. This queuing can play the role of dispersing pedestrians. There are multiple queues for pedestrians to select, and some pedestrians may transfer between queues to choose the shortest queue.

The lifeboat embarkation model can be divided into two stages: the first stage is the passengers preparing to enter the lifeboat through the queue, and the second stage is the passengers selecting seats after they enter the lifeboat. The first stage of embarkation is similar to the queuing process. When passengers arrive at the embarkation area, they will form a queue to wait for the embarkation under the organization of staff or by self-organization. In the process of embarkation, the entrance of lifeboats can be considered as the service point, and passengers can be regarded as having received the queue service as long as they enter the lifeboats. According to the characteristics of lifeboat embarkation, the

M/M/1 model is selected to simulate the embarkation process of passengers in this study. Each lifeboat has two entrances, and a queue is distributed in front of each entrance. Locations of queues are shown in Figure 1. In the initial stage, passengers are assumed distributed in the embarkation area and already wear life jackets. Passengers would move to the nearest lifeboat and form queues at the entrances of lifeboats.

2.2. Types of Embarkation Scenarios. As the capacity of the lifeboat is limited, passengers need to change queues when the lifeboat is full. Passengers generally prefer shorter queues since that can make them enter the lifeboat more quickly, which means that passengers may select the shorter queues by transferring between queues. Families or friends are traveling together on cruise ships, and they usually act in a group. The group passengers tend to preferentially select the same queue or enter the same lifeboat, while individual passengers will directly choose the nearest or shortest queue. Therefore, the transfer behavior can also be divided into transfers between queues of the same lifeboat or queues of all lifeboats. It is often difficult for passengers outside the lifeboat to verify the number of the remaining seats left inside the lifeboat. Hence, it is not beneficial to embark as there are many passengers waiting outside the lifeboat when the capacity of the lifeboat is nearly full. If passengers are under the guidance of the staff, these passengers could transfer among queues by considering the remaining seats of lifeboats.

Once entering the lifeboat, passengers may select seats at random. However, random seating selection may hinder the entry of subsequent passengers because of the narrow interior space of lifeboats. If passengers inside the lifeboat select seats from outboard row to inboard row under the guidance of the staff, then the passenger outside the lifeboat can enter the lifeboat smoothly.

Based on the above analysis, transfer rules of passengers between queues can be divided into four types: transfer between queues of all lifeboats (TAL), transfer between queues that belong to the same lifeboat (TSL), transfer between queues that belong to the same lifeboat based on the seat availability of lifeboats (TSLSA), and transfer between queues that belong to the same lifeboat based on the seat availability of lifeboats (TSLSA). Activity rules of passenger can be divided into four types: the individual passenger selects seats from outboard row to inboard row (ISSOI), the individual
passenger randomly selects seats (IRSS), the group passenger selects seats from outboard row to inboard row (GSSOI), and the group passenger randomly selects seats (GRSS).

The embarkation process is affected by the behavior of passengers, and the characteristic of the behavior of passengers under different rules is disparate. In addition, in order to analyze the difference between individual and group embarkation efficiency, different scenarios are needed to set for individual and group actions, respectively. Therefore, 16 types of embarkation simulation scenarios can be constructed by combining transfer rules and activity rules, as listed in Table 1. Each transfer rule contains four sub-scenarios. The influence of compound rules corresponding to each scenario on embarkation efficiency will be studied. The cabins on cruise ships are generally standard double rooms, and it is common for two people to travel together. Therefore, one group of passengers is composed of two people in this study.

2.3. Parameters of the Embarkation Model

2.3.1. Total Embarkation Time. For the lifeboat embarkation, the embarkation time is the most important index to measure the embarkation process. The total embarkation time includes the time for passengers to arrive at the queue, the waiting time in the queue, and the time for selecting seats in the lifeboat. The total embarkation time under one scenario can be defined as the time when the last passenger completes the embarkation process, as shown in the following equation:

$$\nu_s(i) = \max \left\{ t_{Pax}^{(1)}(i), t_{Pax}^{(2)}(i), ..., t_{Pax}^{(j)}(i), ..., t_{Pax}^{(N_{Pax})}(i) \right\},$$

where $S(i)$ represents the scenario $i$. $N_{Pax}$ represents the total number of passengers. $t_{Pax}(j)^{(i)}$ is the completion time of embarkation of the $j$th passenger in scenario $i$. $\nu_s(i)$ is the total embarkation time when all passengers complete the embarkation in scenario $i$.

2.3.2. Distribution of Numbers of Embarked Passengers within Time Intervals. Since passengers enter lifeboats through different queues, the completion time of embarkation is distributed discretely. In order to analyze the trend of the completion time of embarkation, the total embarkation time is divided into several time intervals, and the distribution of the number of embarked passengers within each interval is counted, as shown in the following equation:

$$N_{PA}^{(k)}(i) = \sum_{l=0}^{6} P_{A}^{D(l)}(S(i), Q(l)), ..., \sum_{l=0}^{6} P_{A}^{D(N_{D})}(S(i), Q(l)),$$

where $D(k)$ represents the time interval $k$. $N_D$ is the number of the time interval. $Q(l)$ represents queue $l$. $\sum_{l=0}^{6} P_{A}^{D(k)}(Q(l))$ represents the number of passengers who enter lifeboats through all queues and complete embarkation during the time interval $k$ in scenario $i$. $N_{PA}^{(k)}(i)$ represents the set of the number of embarked passengers during all of the time intervals in scenario $i$.

2.3.3. Last Transfer Time. When waiting in the queue, passengers will transfer to the queue with fewer people by their preference or transfer to queues of the lifeboat with more empty seats under staff guidance. The timing of transfer out of the queue reflects the tendency of passengers to complete embarkation through the queue. Whether passengers act under their willingness or staff guidance is determined, and the earlier the leaving time of the last transferred passengers of the queue, the sooner the balance would reach between the number of people in the queue and the count of seats remaining in the lifeboat. The time of the last transferred passenger leaving the queue can be expressed as follows:

$$TQ^{Q(i)}(i) = \max \left\{ t_{Q(i)}^{Q(i)}(1), t_{Q(i)}^{Q(i)}(2), t_{Q(i)}^{Q(i)}(3), ..., t_{Q(i)}^{Q(i)}(m), ..., t_{Q(i)}^{Q(i)}(N_{Q(i)}^{(m)}) \right\},$$
where $N_{\text{trans}}^{(l)}$ represents the number of passengers transferred out of queue $l$, $t_{d}^{(l)}(m)$ represents the transfer time of the $m$th passenger in queue $l$ under scenario $i$. $T_{Q}^{(l)}$ is the leaving time of the last transferred passengers in the queue $l$ under scenario $i$, which indicates that the number of passenger in the queue is less than or equal to the count of seats remaining in the lifeboat.

2.3.4. Number of Embarked Passengers through the Queue. The lifeboat has two entrances, and the difference in the number of embarked passengers between two queues can reflect the utilization efficiencies of the two queues. The number of embarked passengers through one of the queues of the lifeboat can be expressed as follows:

$$L_{p}^{L(n)}(v) = \sum_{v=1}^{L(n)} q_{L(n)}^{L(n)}(u) \times L_{p}^{L(n)}(v),$$

where $L(n)$ represents the lifeboat $n$, $N_{p}^{L(n)}$ represents the number of passengers entering lifeboat $n$, $L_{p}^{L(n)}(v)$ represents the $v$th passenger entering the lifeboat $n$, and its value is equal to 1. $q_{L(n)}^{L(n)}(u)$ is the queue $u$ of the lifeboat $n$. If the passengers entering the lifeboat $n$ through queue $u$, $q_{L(n)}^{L(n)}(u)$ equals 1. Otherwise, $q_{L(n)}^{L(n)}(u)$ equals 0. $L_{p}^{L(n)}(u)$ represents the number of people entering lifeboat $n$ through queue $u$ in scenario $i$.

3. Construction of Simulation Model

The embarkation process of passengers is a typical discrete event. AnyLogic [41] is a professional software of virtual prototyping environment for designing complex systems, and it is also widely used to simulate the behavior of pedestrian movement and queuing [42–44]. The software provides API interfaces, and users can customize functions according to the simulation needs. The social force model [45, 46] in the software is based on the Newtonian dynamics, and the different motivations and influences between pedestrians could be reflected by each force. Relevant studies showed that the behavior characteristics of pedestrians in evacuation could be simulated by the social force model, and the model has also been widely used in pedestrian evacuation simulation [47, 48]. Therefore, AnyLogic is used in this study to establish the embarkation scenario and simulate the embarkation process.

3.1. Construction of Simulation Scenarios. The simulation scenario is shown in Figure 2. In order to facilitate the simulation and observation of the embarkation process, the appearances of lifeboats are simplified. Hulls and seating areas of the lifeboat are retained, and passengers can enter the lifeboat through two entrances. Considering the obstruction effect of obstacles on the movement of passengers in the simulation process, the wall module of the software was used to build the hull and seat area. The elements constructed by wall modules can form obstacles in the scenario. Passengers need to go around these elements, and then the movement behavior of passengers in the narrow space of the lifeboat could be simulated. The number of passengers to be embarked is set based on the capacities of lifeboats, and there are 756 passengers in each case of the simulation. This study mainly studies the lifeboat embarkation process of the passengers. The initial condition is that the passengers are already located in the embarkation station and waiting for the captain’s order to embark. The simulation is ended when all passengers have taken seats inside lifeboats.

The type, proportion, and speed of passengers in the evacuation simulation are stipulated in the IMO Guidelines for Evacuation Analysis for New and Existing Passenger Ships [49], as listed in Table 2. The parameters of passengers in the simulation are set according to Table 2.

3.2. Construction of Simulation Processes. Figure 3 shows the logic chart that is defined in the embarkation model. In the AnyLogic software, the logic chart is used to control the actions of pedestrians, and it consists of functional modules and connecting lines. The PedSource module is used to generate passengers. The group form of passengers can be defined in this module. The Lifeboat_Selection module can separate all of the passengers into several crowds, and functions can be called in this module to control crowds to choose the nearest lifeboat. The Output module includes Lifeboat_1_Output, Lifeboat_2_Output, and Lifeboat_3_Output modules, which could allocate passengers to the nearest queue of the current lifeboat. The pedService-Queue module can simulate the queuing behavior of passengers, and this module adopts the rule of first in first out. When passengers enter the double-deck lifeboat, the Level_selection module determines whether passengers select upper or lower seats. Passengers who choose the lower seats will enter the lower level through the pedChangeLevel module. LookingForSeat module can realize the function of seat selection behavior of passengers. The Pedsink module is used to remove passengers from the current simulation scenario. In addition, the Cancel function in the pedServiceQueue module can redistribute transferred passengers to the Output module for the transfer process between queues in one lifeboat. If passengers wish to transfer between all queues, the passengers have been redistributed to the Output module and will be reallocated to the Lifeboat_Selection module once again. Then, the transfer behavior of passengers between all queues can be realized.

In the AnyLogic software, Java can be used to custom items that include functions, parameters, and so on. These
Table 2: The percentage and walking speed of passengers.

<table>
<thead>
<tr>
<th>Passengers</th>
<th>Percentage of passengers</th>
<th>Walking speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Females younger than 30 years</td>
<td>7</td>
<td>0.93</td>
</tr>
<tr>
<td>Females 30–50 years old</td>
<td>7</td>
<td>0.71</td>
</tr>
<tr>
<td>Females older than 50 years</td>
<td>16</td>
<td>0.56</td>
</tr>
<tr>
<td>Females older than 50, mobility impaired (1)</td>
<td>10</td>
<td>0.43</td>
</tr>
<tr>
<td>Females older than 50, mobility impaired (2)</td>
<td>10</td>
<td>0.37</td>
</tr>
<tr>
<td>Males younger than 30 years</td>
<td>7</td>
<td>1.11</td>
</tr>
<tr>
<td>Males 30–50 years old</td>
<td>7</td>
<td>0.97</td>
</tr>
<tr>
<td>Males older than 50 years</td>
<td>16</td>
<td>0.84</td>
</tr>
<tr>
<td>Males older than 50, mobility impaired (1)</td>
<td>10</td>
<td>0.64</td>
</tr>
<tr>
<td>Males older than 50, mobility impaired (2)</td>
<td>10</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Passengers’ information in the queue. Parameters in the purple box are related to the position of seats and entrances of lifeboats. Details of the functions and parameters can be seen in Table S1 of Supplementary Materials.

Figure 3: The logic chart for the embarkation model.

Figure 4: Functions and parameters of the model.
queues and allows passengers to reselect other queues after they leave the longer queues.

Figure 6 shows parameters, the function, and the statechart of the passenger model. Items in the left part of the figure are the function and passengers’ parameters, including ID, location, selected queue, and the wayfinding mode of the passenger. The chart in the right part is related to the current state of the passenger. If the passenger takes a seat, the status of the passenger is changed from standing to seating state by calling this statechart.

The embarkation simulation is run by combining the customized logic chart, functions, and parameters. The specific simulation process is shown in Figure 7, which includes the following steps:

- **Step1:** select simulation scenarios, which include the ways of grouping, the transfer rule, and the preference of seat selection.
- **Step2:** all passengers would be loaded into the simulation scenario, and passengers act alone or in groups based on the selected type of group.
- **Step3:** passengers choose the nearest lifeboat and form queues at the entrances of the lifeboat. In group mode, passengers in the same group would select the same queue.
- **Step4:** based on the selected scenario, passengers move forward in the queue and prepare to transfer between queues belong one lifeboat or all queues.
The embarkation characteristics of passengers were analyzed through simulations of 16 types of embarkation scenarios, and each scenario was run 100 times. The values in Figures 9–12, and S1 are mean values of the 100 simulation experiment results, and the error bars represent the standard deviation of the results.

4.1. Analysis of the Total Embarkation Time. Figure 9 shows the total times for passengers to complete embarkation in 16 types of scenarios. For scenarios of individual passengers, the embarkation time in the TAL-IRSS scenario is the longest, while the TSLSA-ISSOI scenario is the shortest. The total embarkation time of the TAL-IRSS and TSLSA-ISSOI scenarios is 1100 and 739 seconds, respectively, and the time of the TSLSA-ISSOI scenario is 32.8% less than that of the TAL-IRSS scenario. In scenarios of group passengers, scenarios that have the longest and shortest total embarkation time are the TAL-GRSS and TSLSA-GSSOI. The total embarkation time of the TAL-GRSS and TSLSA-GSSOI scenarios is 1199 and 891 seconds, respectively, and the time of the TSLSA-GSSOI scenario is 25.7% less than that of the TAL-GRSS scenario. It shows that values of total embarkation time were affected by transfer and activity rules.

From the perspective of transfer rules, the total embarkation time of the four subscenarios contained in TSL and TSLSA rules was smaller than the corresponding sub-scenarios under TAL and TALSA rules, respectively. It can be found that the embarkation efficiency of passengers transfer between queues of the same lifeboat was higher than they randomly transfer between all queues. The reason may be that the transfer between queues of the same ship can keep the balance of the number of people in these queues preferentially, which could improve the embarkation efficiency of the current lifeboat.

The total embarkation time of subscenarios under TSLSA and TALSA rules was shorter than that of TSL and TAL rules, respectively. This result indicated that transfer between queues based on the seat availability of lifeboats could reduce the behavior of passengers blindly moving to a lifeboat that has shorter queues but fewer remaining seats. In the same transfer rules, the total embarkation time of IRSS and ISSOI rules was smaller than that of GRSS and GSSOI rules, respectively, showing that the embarkation efficiency of the individual passenger is higher than that of the group passenger. In addition, the total embarkation time of IRSS and GRSS rules was longer than that of ISSOI and GSSOI rules, respectively, demonstrating that passengers could complete embarkation earlier if they select seats from outboard row to inboard row.

4.2. Distribution Analysis of Numbers of Embarked Passengers within Time Intervals. Figure 10 shows the number distribution of embarked passengers within time intervals. Before 200 seconds, the embarkation completion rate of IRSS,
GRSS, ISSOI, and GSSIO rules is a little distinction under the four transfer rules. Within 200–600 seconds, the results of IRSS, GRSS, ISSOI, and GSSIO under different transfer rules gradually began to show obvious differences, which indicated that the embarkation efficiency was impacted by the transfer behavior of passengers. Moreover, the number of embarked passengers in the four subscenarios of TSLSA and TALSA rules was greater than that in the scenarios of

![Diagram of passenger embarkation simulation process]

**Figure 7:** The process of passenger embarkation simulation.
TSL and TAL rules during this period. This phenomenon demonstrated that the queue transfer considering the seat availability of lifeboats could improve the embarkation efficiency of passengers, which was consistent with the result in Figure 9.

In all scenarios, the peak time of passengers’ completed embarkation was around 100 seconds when they acted alone, and slightly more than 200 seconds when they acted in groups. The peak time in the two action modes was both in the early stage of the embarkation process. Figure 13 shows snapshots of the embarkation process. In Figure 13(a), the number of passengers in the lifeboat was small at the initial stage of the embarkation process, and passengers could quickly enter the lifeboat and take seats. In Figure 13(b), passengers at the entrance cause obstacles to subsequent entering passengers as the embarkation process progresses, which reduced the number of embarked passengers per unit time. Therefore, the embarkation efficiency would decrease as the number of passengers increased inside the lifeboat at the initial stage of the embarkation process. While in the middle stage of the embarkation, the number of embarked passengers decreased also related to the lifeboat 2. Lifeboat 2 can be filled earlier for its capacity is small. When lifeboat 2 is full, the number of passengers who could complete the embarkation would be decreased in unit time. Thus, the embarkation efficiency at this stage was also related to the state of lifeboats. As shown in Figure 10, the number of embarked people within 300-500 seconds suddenly decreased.

**Figure 8:** Snapshots of the embarkation simulation. (a) The passengers form queues. (b) The passengers transfer between queues. (c) The passengers take their seats in the lifeboat.

**Figure 9:** Total embarkation times of passengers.
4.3. Analysis of the Last Transfer Time. Figure 11 shows the time of the last transferred passenger leaving the queue. In all scenarios, the last transfer times of queues 3 and 4 were significantly smaller than that of the other queues. Queues 3 and 4 belonged to lifeboat 2, and the capacity of this lifeboat was the smallest that could be filled full quickly. Therefore, the excess passengers in these two queues could be transferred to other queues earlier. Under TSL and TAL rules, the last transfer time of queues 3 and 4 was equal, indicating that excess passengers of two queues were transferred out simultaneously as long as lifeboat 2 was full.

In TSLSA and TALSA rules, passengers in these two queues would be gradually transferred to other queues in advance due to the consideration of the seat availability of lifeboats. Therefore, there may be a distinction in the process of passengers transferring out from these two queues, resulting in the difference in the last transfer time between these two queues. The last transfer time of queues 2 and 5 was significantly longer than that of the other queues. These two queues belonged to lifeboats 1 and 3, respectively. As these two queues were close to lifeboat 2, passengers in queues 3 and 4 would choose queues 2 and 5 as the prime target queues for transfer. Therefore, the number of passengers in the queues 2 and 5 was more than in queues 1 and 6, resulting in that the last transfer times of these two queues were also later than other queues.
4.4. Analysis of the Distinction in the Number of Embarked Passengers between Two Queues of Each Lifeboat.

Figure 12 shows the distinction in the number of embarked passengers between two queues of each lifeboat. Each cylinder represents the ratio of the number of embarked passengers from two queues of one lifeboat. The lower part of the cylinders of lifeboats 1, 2, and 3 represents the proportion of the number of embarked passengers entering through queues 1, 3, and 5, respectively. Conversely, the upper part of the cylinder represents queues 2, 4, and 6, respectively.

In most scenarios, the number of embarked passengers entering through queues 2 and 5 was more than that of queues 1 and 6. Especially for the TSL-GRSS, TSL-GSSSOI, TAL-GRSS, TAL-GSSSOI, TALSA-GRSS, and TALSA-GSSSOI scenarios, the difference in the proportion of embarked passengers between the two queues belonged to the same lifeboat was more pronounced. This distinction was
mainly reflected in that there were more embarked passengers in queues 2 and 5 than in queues 1 and 6, which was consistent with the result in Figure 11. Compared with TAL and TALSA rules, the ratio of two parts of the cylinder under TSL and TSLSA rules was closer to 50%. As known from Figure 9, the total embarkation time of the four subscenarios under TSL and TSLSA rules was shorter than that under TAL and TALSA rules, respectively. It showed that the balance of the number of passengers in queues belong one lifeboat could be better maintained if passengers transfer between queues of the same lifeboat, which could also improve the embarkation efficiency.
5. Conclusions and Future Works

This study examined the lifeboat embarkation process of cruise passengers. By dividing the embarkation process into queuing and seat selection stages, transfer rules of queue and activity rules of the passenger were proposed. Based on the rules, 16 types of embarkation scenarios were constructed, and embarkation processes of these scenarios were simulated.

The simulation results showed that the embarkation efficiency of passengers was high in the early stage. As the progress of the embarkation, the passengers who had entered the lifeboat caused obstacles to the subsequent passengers, and the embarkation efficiency was gradually decreased. It was advantageous for passenger embarkation to select seats from outboard row to inboard row than select seats by random. The embarkation efficiency of passengers transfer between queues of the same lifeboat was higher than they randomly transfer between all queues. In addition, the embarkation efficiency would be improved again if the queue transfer was based on the seat availability of lifeboats. An obvious result of the study is that the total embarkation time of the TSLSA-ISSOI scenario is 32.8% less time than the TAL-IRSS scenario, and the total embarkation time of the TSLSA-GSSOI scenario is also 25.7% less than the TAL-GRSS scenario.

We also tested the embarkation time of passengers under the mixed rule, as shown in Figure S1. The mixed rule combines all transfer and seat selection rules, and it mainly reflects that some of the passengers acted autonomously under the guidance of the staff. The results show that the embarkation time under the mixed rule is longer than the single rule under the guidance of the staff (TSLSA-ISSOI and TSLSA-GSSOI) and shorter than the single rule under the autonomous action of passengers (TAL-IRSS and TAL-GRSS). Even if some of the passengers still kept their own willingness and did not act on staff guidance, the embarkation efficiency is still higher than that without the guidance of the staff. It is proved that under the guidance of the staff, appropriate queue transfer and seat selection rules can effectively improve the embarkation efficiency of passengers.

The limitation of this study is that the simulation result has not been compared with experimental data of the object ship. In order to perfect the rules proposed in this study and apply them to improve the embarkation efficiency of cruise ships, it is necessary to carry out passenger embarkation experiments and use experimental data to improve the queue transfer and seat selection rules in future work.

Data Availability

The data used to support the findings of this study are available upon request to the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

Detailed information on Table S1 and Figure S1 is presented in the supplementary materials as follows: (1) Table S1: details of the functions and parameters in the model. (2) Figure S1: the embarkation time of passengers under mixed rule. (Supplementary Materials)

References


