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2 **Analysis of Human Competitive Behavior on an**  
3 **Inclined Ship**

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6 **Abstract:** When a ship accident occurs, emergency evacuation of passengers in a  
7 shorter time is one of the most effective means of reducing casualties. However, in  
8 addition to the ship inclination, the efficiency of the emergency evacuation can be  
9 affected by human behaviour (*e.g.* competitive behaviour), which affects human  
10 moving speed. Therefore, to analyse the impact of competitive behaviour during ship  
11 evacuations, a dynamic evaluation system is developed to measure nested competitive  
12 behaviour. Firstly, the perceived area is obtained by dividing the pedestrian visual  
13 perspective, which is used to calculate crowd density at every time step. Secondly,  
14 fuzzy logic is used to calculate the real-time competitive degree based on the inclined  
15 angle and crowd density, integrated into the human evacuation model as an input  
16 parameter to update competitive behaviour. Finally, this study analyses and evaluates  
17 evacuation time and efficiency with different proportions of competitive people at  
18 different inclined angles, using a dining room on a ship as a case study. The results  
19 show that, without ship inclination, the total evacuation time decreases with the increase  
20 of the proportion of competitive people as more competitive people can speed up the  
21 evacuation process. While the inclination of a ship leads to a decrease in human walking  
22 speed, congestion at the exit, and a slower overall evacuation process. According to the

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23 findings of this study, an appropriate increase in the proportion of competitive human  
24 is beneficial to the efficiency of emergency evacuation. And strengthening the guidance  
25 at the exit will also reduce the evacuation time.

26

27 **Key words:** Maritime Safety; Competitive Behaviour; Emergency Evacuation; Social  
28 Force Model; Ship Inclination.

29

## 30 **Introduction**

31 In recent years, the cruise tourism market has been expanding in line with  
32 economic development. The increasing number of passengers and market demand lead  
33 to the large size of passenger ships, resulting in more safety issues. Particularly, once  
34 an accident occurs during the operation of a passenger ship, it often leads to serious  
35 casualties and property damage(Cao et al., 2023b; Huang et al., 2023a). Therefore, to  
36 improve the safety level of passenger ships, IMO has put forward a series of evacuation  
37 requirements for passenger ships. According to the requirements of MSC.1/Circ.1533,  
38 ships built after 1 January 2020 should be carried out the evacuation analysis (IMO,  
39 2016). At the same time, to study the characteristic human movement parameters and  
40 evacuation efficiency during ship evacuation, some researchers have also conducted a  
41 series of experiments (Liu et al., 2022; Wang et al., 2021c; Wang et al., 2021d).  
42 Although theoretical analysis has been developed, for safety reasons, it is still  
43 unrealistic to carry out ship evacuation experiments in a real emergency. Therefore, the  
44 existing evacuation experiments will have biases with reality as they are carried out in  
45 non-emergency situations, which affects the validity of the results to a certain extent.

46 With the continuous development of computer modelling techniques, evacuation  
47 model simulation has highlighted the significant advantages (Fang et al., 2023). In  
48 existing studies, evacuation models are mainly classified into macro-models and micro-  
49 models based on the modelling scale, and have been studied in detail in large gathering  
50 places such as land buildings or stations (Haghani, 2020a, b). Macro-models mainly  
51 provide theoretical support for managers in the formulation of evacuation strategies and  
52 the calculation of available evacuation time, such as fluid-dynamic model (Wang and  
53 Jia, 2022). Micro-models primarily concentrate on characterizing individual attributes  
54 and the interactive behaviours between individuals and their environments. These  
55 models offer a chance for studying complex evacuation systems, with cellular automata  
56 and the social force model being particularly popular choices (Ntzeremes et al., 2020).  
57 Notably, the social force model, as a representative continuous simulation model, has  
58 been used in various commercial evacuation software. This means that, through the

59 secondary development of existing evacuation software, the continually refined social  
60 force model can be employed in more complex and extensive evacuation scenarios,  
61 achieve a wider range of applications. Given these advantages, the social force model  
62 is selected as the evacuation model for this study, with the intention of facilitating  
63 comprehensive human evacuation analysis on ships in future research endeavours.

64 However, compared with the mature field of land-based evacuation, the human  
65 evacuation onboard ships required the consideration of many specific factors, such as  
66 the assembly station, the type of ship accident and the life-saving equipment, etc. These  
67 influencing factors not only put forward new requirements for evacuation modelling  
68 but also lead to a wide range of heterogeneous behaviours during the evacuation process  
69 (Arshad et al., 2022; Cao et al., 2023a; Wang et al., 2022). While heterogeneous  
70 behaviours have garnered growing attention from researchers, and certain studies have  
71 highlighted their potential to either facilitate or impede overall evacuation processes,  
72 less attention has been directed towards investigating the impact of such heterogeneous  
73 behaviours on shipboard evacuations. The questionnaire surveys have revealed that  
74 owing to the complex layout of ships and the unique evacuation procedures involving  
75 lifeboat embarkation or other life-saving equipment, a significant portion of passengers  
76 admit to experiencing nervousness, fear, and other emotions. It is confirmed that the  
77 likelihood of heterogeneous behaviours occurring during ship evacuations is  
78 heightened at a psychological level (Galán, 2021; Huang et al., 2023b; Wang et al.,  
79 2021a; Wang et al., 2023; Wang et al., 2021e). In addition, existing research has shown  
80 that human often exhibit competitive behaviours during shipboard evacuations,  
81 especially in emergencies, where they are more likely to engage in typical competitive  
82 behaviours such as overtaking, pushing, and running(Wang et al., 2020). For example,  
83 by investigating the Costa Concordia accident, Bartolucci found that people always  
84 showed more competitive behaviour when boarding lifeboats, and that as the ship tilted  
85 more and more due to water ingress, more and more people showed 'panicky'  
86 behaviours (Bartolucci et al., 2021). The above studies have analysed the human  
87 competitive behaviour from the perspective of psychology or sociology, while most  
88 studies still lack the detailed information in the modelling and implementation process,

89 which leads to a gap between the model and the underlying theory.

90 To fill the gaps in the current research, it is necessary to determine the human  
91 competitive behaviour in conjunction with the type of ship accident or the severity of  
92 the accident when building an evacuation onboard ships model, which is able to analyse  
93 more accurately the impact of human behaviour factors during the evacuation process.  
94 Therefore, this study aims to analyse the evacuation efficiency in different scenarios by  
95 building a human evacuation onboard ships model specifically designed for onboard  
96 ships. This model incorporates a dynamic assessment system to account for nested  
97 competitive behaviour, particularly in the context of ship water ingress accidents. Based  
98 on the ship inclined angle and the crowd density in the individual's perception area, the  
99 improved model uses a fuzzy system to calculate the real-time competition level of  
100 competing passengers. This calculation is then integrated into the evacuation model as  
101 an input parameter to update and simulate the competitive behaviours of people during  
102 evacuations.

## 103 **Related works**

### 104 **Evacuation on inclined ships**

105 The high tendency of ships to exhibit an inclined attitude after an accident at sea,  
106 as in the case of the “Costa Concordia” and “Sewol”, means that the effects of ship  
107 inclination on human movement must be taken into account when studying the  
108 evacuation onboard ships(Wang et al., 2021b). When evacuating an inclined ship,  
109 human need to adjust their body state in order to maintain normal walking, while this  
110 adjustment is at the expense of speed. To measure the walking speed in inclined ships,  
111 the researchers have carried out a series of experiments on the human walking.

112 Researchers at the Research Institute of Maritime Engineering and the National  
113 Maritime Research Institute of Japan tested human movement parameters when the ship  
114 was inclined in a combination of corridor simulators and real ship experiments. They  
115 found that not only human walking speed decrease when the ship was inclined, but  
116 human also wanted to keep a distance from each other more than when the ship was  
117 floating on even keel (Murayama et al., 2000). The researchers of the Australian

118 Maritime Engineering Cooperative Research Centre found that in the case of small  
119 inclination, the human speed going downhill along the incline direction increased with  
120 the increase of the inclined angle, while the influence of heeling and uphill on the speed  
121 was not significant. But when two people walk side by side, their speed is lower than  
122 when they walk alone (Brumley and Koss, 1998). Researchers at the Netherlands  
123 Organization for Applied Scientific Research organised experiments in a ship motion  
124 simulator and found that the slope had a greater effect on human speed when facing  
125 uphill than downhill, but that handrails were effective in helping to walk (Bles et al.,  
126 2001). In contrast, researchers at the Korea Research Institute of Ships and Ocean  
127 Engineering did not agree with this conclusion. After conducting experiments using a  
128 corridor simulator, due to psychological factors and the angle of incline, they found that  
129 the human speed decreased rather than increased when traveling downhill (Lee et al.,  
130 2004). In addition, Sun et al. (2018) built a two-degree-of-freedom inclined ship  
131 corridor simulator. They concluded that when the inclined angle was less than  $10^\circ$ ,  
132 human would be affected by gravity resulting in an increase in walking speed.  
133 Compared to trimming angle, the same heeling angle had the least effect on human  
134 speeds.

135 Since there is no clear standard for the experimental scenarios and experimental  
136 conditions, and the exercise ability of the participants in the experiment is quite  
137 different. As a result, the conclusions drawn from the above experiments are also quite  
138 different. At this stage, to enrich the results of the evacuation experiments, some human  
139 movement models in inclined ships have been proposed. In these studies, evacuation  
140 models are mainly used to carry out continuity calculation, so as to more systematically  
141 show the influence of the inclination effect on the human movement. By improving the  
142 common evacuation model, Kang et al. (2019) improved the basic social force model  
143 based on pedestrian dynamics, and analysed the influence of ship inclination on human  
144 walking in different moving directions. Fang et al. (2022) developed a human  
145 evacuation model in terms of reanalysing the force applied to human in the inclined  
146 ship, and applying it to the full-size evacuation simulation. The Hamburg Ship Model  
147 Basin Newsletter in Germany submitted a report to IMO containing an estimated

148 function of the human speed at different inclined angles, which also considered the  
149 variability of human walking on corridors and staircases (Valanto, 2006). Kim et al.  
150 (2019) developed a simulation model for the disaster of the “Sewol” by focusing on the  
151 analysis of the human density and the congested area. This study compared the change  
152 of the evacuees in the evacuation simulation and real accident as well as predicted the  
153 casualties.

## 154 **Competitive behaviour during evacuation**

155 During land-based personnel evacuation, real evacuation videos and experimental  
156 footage have documented the human competitive behaviour. Many studies have  
157 focused on the impact of human competitive behaviours on evacuation efficiency. Cao  
158 et al. (2021) simulated the human evacuation from exits of different sizes considering  
159 human competitive and cooperative behaviours, respectively. Moreover, the arching  
160 phenomenon was observed as crowd gathered at the exit. von Schantz and Ehtamo  
161 (2019) redefined the human local decision-making model using a spatial game approach  
162 and elaborated on the cause of the arching phenomenon at bottlenecks. They found that  
163 the competition led to an increase in the internal force of the crowd, which makes it  
164 prone to accidents of falling and stepping accidents. Hidalgo et al. (2017) proposed an  
165 elliptical human shape based on real experiments, and the accuracy of the simulation  
166 model was improved by adding rotation movements. Meanwhile, they proposed a  
167 strategy to reduce the congestion time at the exit. Zheng and Cheng (2011) proposed a  
168 model including human cooperation and competition behaviour based on game theory.  
169 Their results showed that human competitive behaviour was related to the degree of  
170 urgency during evacuation and too low competition ratios would reduce the evacuation  
171 efficiency. Gao et al. (2016) modified the exclusionary force of corners on human to  
172 reflect the human competition degree through collision avoidance behaviour.  
173 Comparing the experimental results, the improved model was verified to be able to  
174 effectively predict the human collision avoidance behaviour at different competitive  
175 levels.

176 However, due to the special marine operating environment and limited evacuation

177 space, it is difficult to obtain real video footage from the accidents for studies on the  
178 human evacuation onboard ships. To fill this gap, Kvamme (2017) analysed the “Costa  
179 Concordia” accident report in detail and found that a higher number of competitive  
180 behaviours increased the likelihood of secondary disasters. This study argued that it  
181 was necessary to consider human behaviours in ship evacuation models. Bartolucci et  
182 al. (2021) interviewed survivors of the accident and counted the probability of  
183 heterogeneous behaviours in different locations and at different moments. The results  
184 showed that competitive behaviours were likely to appear in special space, especially  
185 when boarding lifeboats, which was admitted by the majority of the people. By  
186 comparing the effects of different proportions of competitive people on evacuation  
187 efficiency, Kang et al. (2019) found that the inclusion of a small number of competitive  
188 human could reduce evacuation time, while too large proportion may show a negative  
189 impact on evacuation efficiency. Wang et al. (2020) surveyed 1380 passengers, 44% of  
190 the participants said that they were likely or very likely to have competitive behaviour.  
191 Especially in emergency situations, passengers would more tend to complete  
192 evacuation quickly. However, when people did not feel the existence of danger, they  
193 would have a higher proportion of solidarity and cooperation in the evacuation process.

## 194 **Research gaps and contributions**

195 An extensive literature review found that there is still a gap in evacuation models  
196 that take into account the human competitive behaviours. Although, some studies have  
197 attempted to analyse human behaviours during human evacuation onboard ships  
198 through simulation models, most of them referred to results of land-based human  
199 evacuation, which does not connect ship accidents with competitive behaviour.  
200 Moreover, these studies often categorize individuals as either exhibiting competitive  
201 behaviours or not, using an all-or-nothing approach that fails to capture the nuanced  
202 evolution of competitiveness throughout the entire evacuation process. In reality, the  
203 level of human competitiveness continuously fluctuates in response to environmental  
204 factors during an evacuation. Therefore, it becomes imperative to assess  
205 competitiveness dynamically in real-time, taking into account the emergency severity

206 of the evacuation (accident severity) and crowd density when simulating human  
207 competitive behaviours. This dynamic approach is essential for ensuring that simulation  
208 results closely align with real-world scenarios. Based on this, to fill the existing research  
209 gap, this study proposes a ship evacuation model with a nested human competitive  
210 degree assessment system and analyses the human evacuation results of different  
211 inclined angles by simulating the evacuation scenario of a single-exit room. The  
212 contribution of this study is:

213 a) The competitive degree is introduced into the evacuation model by improving  
214 a real-time assessment system of human competitive desires. Using fuzzy system theory  
215 calculates the competitive degree in each time step based on the inclined angles and the  
216 density in the perceived area of the competitive people.

217 b) By dividing the pedestrian visual perspective, the area within the competitive  
218 people perspective and a small blind area are set as the perceived area. The competitive  
219 people calculate the crowd density at every time step according to the number of people  
220 counted in the perception area. This redefined pedestrian perspective can more closely  
221 describe the impact of people around them on competitive people.

222 c) By setting different inclination angles, the evacuation performance of different  
223 competitive degree is analysed and evaluated. Common evacuation phenomena can be  
224 effectively observed, and more importantly, counting the time interval between two  
225 consecutive people passing through the exit can help us better understand the  
226 evacuation process from the qualitative aspect.

## 227 **Methodology**

228 In this study, the simulation process is primarily comprised of three key  
229 components: the dynamic assessment system for evaluating human competitiveness, an  
230 evacuation model designed for human evacuations on inclined ships, and the resultant  
231 data, as illustrated in Fig. 1. At the outset of the simulation, a fuzzy system is employed  
232 to calculate the degree of human competition, taking into account factors such as the  
233 number of competitive individuals and the degree of ship inclination. These calculated  
234 results are then used as parameters within an enhanced social force model. Subsequently,

235 the simulation outcomes are generated through interactions involving collision  
 236 avoidance and competitive behaviours among individuals within the crowd. These  
 237 interactions serve to continually update the evacuation status and the locations of the  
 238 individuals involved.

### 239 **Social force model for inclined ship**

240 The social force model is a popular microscopic evacuation model that is known  
 241 for its reliability and compatibility. It is widely used to predict and optimize crowd  
 242 evacuation during emergencies and disasters, with the goal of improving the safety and  
 243 survival rate of individuals. The social force model is a unique combination of  
 244 psychological aspects of pedestrian movement and Newtonian mechanics. It is initially  
 245 introduced by Helbing for the purpose of evacuation modelling and has been widely  
 246 used to explain pedestrian self-organization phenomena, including the bottleneck effect  
 247 and "fast is slow". The model has been further improved to cater to the study of crowd  
 248 dynamics in various contexts (Helbing and Molnar, 1995). The social force model is  
 249 primarily based on the physical forces and psychological changes of individuals. It  
 250 takes into account factors such as the self-driven force generated by the attraction of  
 251 the target exit, pedestrian-pedestrian and pedestrian-boundary forces, and random  
 252 forces. By using parameter settings, the model prompts pedestrians to move with the  
 253 combined force of these physical and psychological forces. The direction of pedestrians'  
 254 movement is not restricted, allowing for slight overlapping between pedestrians due to  
 255 overcrowding, which is a common occurrence in real-life emergency situations. The  
 256 social force model expresses crowd dynamics as shown in Eq. (1).

$$257 \quad m_i \frac{d\mathbf{v}_i}{dt} = \mathbf{f}_{will} + \sum_{j(j \neq i)} \mathbf{f}_{ij} + \sum_W \mathbf{f}_{iW} + \boldsymbol{\xi} \quad (1)$$

258 where,  $m_i$  represents the mass of pedestrian  $i$ ,  $\mathbf{v}_i$  is the real-time speed of pedestrian  
 259  $i$ , and  $t$  is adjustment time.  $\mathbf{f}_{will}$  is the desired force, which represents the attraction effect  
 260 of the target on the pedestrian's moving direction;  $\mathbf{f}_{ij}$  and  $\mathbf{f}_{iW}$  represent the interaction  
 261 between other pedestrians  $j$  and obstacles or walls and pedestrian  $i$ , respectively, which  
 262 is mainly to achieve collision avoidance between pedestrians and between pedestrians

263 and obstacles.  $\zeta$  is the random force.

264 The dynamics of pedestrian evacuation in an inclined ship have been fully  
265 discussed in previous studies. Compared to walking on flat terrain, pedestrians are  
266 affected by the ship inclined force  $f_b$ , and this force always point from the high terrain  
267 to the low terrain. At the same time, to overcome negative effect of the inclined ship on  
268 walking, human may take actions such as grasping the railings and adjusting their body  
269 weight in the inclined scenario. In the force model, such actions are realized by the self-  
270 adjustment force  $f_{adj}$  (Fang et al., 2022; Jiang et al., 2022). Therefore, the pedestrian  
271 movement in the inclined ship space is shown in Eq (2):

$$272 \quad m_i \frac{dv_i}{dt} = f_{will} + \sum_{j(j \neq i)} f_{ij} + \sum_W f_{iW} + f_b + f_{adj} + \zeta \quad (2)$$

## 273 **Competitive behaviour**

274 Most existing studies on human competitive behaviour often revolve around the  
275 concept of individuals seizing target points, particularly in discrete models like the  
276 cellular automata model. These models offer a simpler way to describe competitive and  
277 cooperative behaviours. However, one limitation is that in the cellular automata model,  
278 the movement directions of individuals tend to be relatively fixed. This can result in  
279 competitive individuals failing to secure their desired positions during the simulation.

280 In contrast, the social force model characterizes human movement through force,  
281 without the direct setting of specific human movement parameters. This means that the  
282 social force model relies on fewer variables, resulting in more robust simulation  
283 outcomes. Although the task of seizing target points can be achieved in force-based  
284 models by extrapolating future time steps, this approach transforms the social force  
285 model from a continuous model into a discrete one. This transformation is less than  
286 ideal as it significantly increases the computational demands of the model and causes  
287 it to lose some of the crowd aggregation characteristics that are preserved in the  
288 continuous model. In fact, competitive behaviour expresses the desire of people to reach  
289 the goal point faster, which means that the desired speed of competitive people  
290 increases continuously with their competitive degree (Cao et al., 2021; Sticco et al.,

291 2022; von Schantz and Ehtamo, 2019). Eq. (3) explains the calculation of desired force  
292 in the base social force model.

$$293 \quad \mathbf{f}_{will} = m_i \frac{v_i^0(t) \mathbf{e}_i^0 - \mathbf{v}_i(t)}{\tau} \quad (3)$$

294 where,  $v_i^0(t)$  is the desired velocity of the pedestrian  $i$ ,  $\mathbf{e}_i^0$  is the target direction of the  
295 pedestrian,  $\mathbf{v}_i(t)$  is the real-time speed of the pedestrian  $i$  at moment  $t$ , and  $\tau$  is the  
296 reaction time. The desired force is the main driving force for the human movement,  
297 which is driven by the mode that the human needs to adjust the magnitude and direction  
298 of his/her real-time velocity to the desired velocity and desired direction as much as  
299 possible within the reaction time.

300 Extensive research has found that the emergence of competitive behaviours among  
301 people is largely dependent on the surrounding environment. Especially, when there is  
302 little escape time available, the likelihood of exhibiting competitive behaviours and the  
303 desire to compete is greater in a crowd (von Schantz and Ehtamo, 2019). In addition,  
304 the density of surrounding people can also have an impact on human competitive  
305 psychology. Close proximity and slow movement speeds between individuals in  
306 congestion areas can lead to the emergence of more competitive behaviours. (Sun and  
307 Liu, 2021). However, the human competitive behaviour is not influenced by all the  
308 people around them but is determined by the density in the perceived area. According  
309 to (Fang et al., 2021), the competitive people field of view angle is set to  $120^\circ$  and the  
310 radius of the field of view is 2 m in this study. Meanwhile, the range of 0.5 m within  
311 the blind spot of the view field is also set to be the perceived area because human who  
312 are nearer at the rear can be sensed through sound and other means in real life. As shown  
313 in Fig. 2, human need to be screened to determine the number of potentially affected  
314 pedestrians when calculating the density of people around them. The light-colored area  
315 in Fig. 2 is the perceived area of the pedestrians, and the dark-colored area is the blind  
316 area of their field of view.

317 Due to the rapidly changing situation during the evacuation process, the level of  
318 competition among people is also uncertain at any given moment. A quantitative value  
319 is used in previous studies to constant whether human have competitive behaviours or

320 the competitive degree (Lin et al., 2019), while this method is inaccurate in the actual  
 321 evacuation process. Therefore, this study proposes a fuzzy system based on the inclined  
 322 angles and the density of people to calculate the competitive degree at each moment, as  
 323 shown in Fig. 3. A fuzzy inference system is a collection of fuzzy sets, fuzzy affiliation  
 324 functions, and fuzzy rules used to simulate the decision-making process, including three  
 325 phases of fuzzification, inference, and defuzzification (Yang et al., 2020). The  
 326 fuzzification stage converts the input values of clear inclined angle and density into  
 327 fuzzy affiliation values by means of fuzzy sets and fuzzy affiliation functions. Based  
 328 on the database and rule base, the defuzzified inputs are used to calculate the defuzzified  
 329 outputs using decision units in the inference stage. Finally, in the defuzzification stage,  
 330 the fuzzy sets and fuzzy affiliation values of the output variables are converted into  
 331 clear values. In this system, the Mandani inference method is used to construct the fuzzy  
 332 implication relation by the Cartesian product of fuzzy sets. The defuzzification process  
 333 is calculated using the Centroid method, which involves determining the centre of  
 334 gravity of the area bound by the output affiliation curve and the horizontal axis. This  
 335 value is then used as the output value of the fuzzy inference system to adapt to small  
 336 input signal variations.

337 The expressions of fuzzy rules and fuzzy implications are shown in Eqs. (4) and  
 338 (5):

$$339 \quad R_i = (A_i \text{ and } B_i) \rightarrow C_i \quad (4)$$

$$340 \quad \mu_{R_i} = [\mu_{A_i}(x) \text{ and } \mu_{B_i}(y)] \rightarrow \mu_{C_i}(z) \quad (5)$$

341 where  $A_i$  denotes the fuzzy set of inclined angles,  $B_i$  denotes the fuzzy set of density,  $C_i$   
 342 denotes the fuzzy set of competitive degree,  $R_i$  is the fuzzy relationship matrix.  $\mu$  is the  
 343 affiliation of the input and output parameters.  $x$ ,  $y$ , and  $z$  denote the semantics of the  
 344 inputs and outputs correspondingly.

345 In the input, the fuzzy variable  $A_i$  for inclined angle has three linguistic values (S-  
 346 small, M-medium, L-large); the fuzzy variable  $B_i$  for density also has three linguistic  
 347 values (L-low, M-medium, H-high); and the competitive degree  $C_i$  has five linguistic  
 348 values (VS-very strong, S-strong, M-moderate, W-weak, and VW-very weak). Based

349 on the design principle of fuzzy rules and the experience of observing human  
 350 competitive behaviours, people tend to quickly leave the current area when the angle of  
 351 inclination is very steep or the density of people in their field of view is high. This  
 352 behaviour helps to avoid further congestion or severe overcrowding caused by the  
 353 congregation of people or seriousness of inclination. The fuzzy set of input variables  
 354 can be listed as  $3 \times 3 = 9$  rules, and the detailed rules for assessing the competitive degree  
 355 are shown in Table 1. Taking the first rule as an example, if the inclined angle belongs  
 356 to the set "Small" and the density belongs to the set "Low", then the competition degree  
 357 belongs to "Very Weak". In addition, Fig. 4 displays the logical operations of the fuzzy  
 358 rule. The yellow area represents the input inclined angle and density parameters'  
 359 affiliation to each set, and the blue area shows the output competitive degree's affiliation  
 360 to each set. To perform mathematical operations in the evacuation model, it's necessary  
 361 to convert the competitive degree into numerical values through defuzzification. Fig. 5  
 362 illustrates the competitive degree of people in various situations. As observed, the  
 363 competitive degree increases with an increase in the inclined angle and density of  
 364 people in the perceived area.

365 The results of the calculations mentioned above indicate the need to update the  
 366 desired speed of competitive individuals in real-time, based on their competitive degree  
 367 in the model. The expression of the social force model shows that the desired speed of  
 368 competitive people usually increases exponentially with an increase in their competitive  
 369 degree, as depicted in Fig. 6 (Cao et al., 2021). In this study, the normal desired velocity  
 370  $v_i^0(t)$  is set to 1.3 m/s, and the desired velocity of the competitive people is calculated  
 371 by Eq. (6):

$$372 \quad v_c^0(t) = v_i^0(t) \{1 + \exp[m\chi_i(t) - n]\} \quad (6)$$

373 where,  $v_c^0(t)$  is the desired velocity of the competitive people,  $\chi_i(t)$  is the competitive  
 374 degree of pedestrian  $i$  in the moment  $t$ .  $m$  and  $n$  are constants.

375 Fig. 7 provides a brief overview of the model execution and the human movement  
 376 procedure. The model determines whether individuals exhibit competitive behaviour or  
 377 not based on the input the proportion of competitive people. At each time step,

378 individuals with competitive behaviour are required to identify potentially influential  
379 crowds around them and update their degree of competitiveness and desired speed  
380 accordingly. The evacuation model then updates and stores the positions and speeds of  
381 all evacuees by calculating the combined forces until everyone has been evacuated.

## 382 **Simulation results and discussion**

### 383 **Case scenarios setting**

384 The dining room of a ship is chosen as the evacuation scenario in this study, which  
385 is a square with a side length of 15 m and a exit width of 1 m. Due to the limited space  
386 of the ship, this room also serves as a recreational facility for passengers, a large number  
387 of people gather for an extended period. Therefore, this room is selected to highlight  
388 the effect of inclined ships on human movement and effectively characterize onboard  
389 ship evacuations, particularly the heterogeneous behaviour of competitive people. Fig.  
390 8 illustrates the initial distribution of people in the model, where the initial assumptions  
391 of the proportion of competitive people  $\alpha$  is 0.5. The red circles represent competitive  
392 people, the blue circles represent normal individuals, and the size of the circles  
393 represents different individuals' size. It's worth noting that parameters such as radius,  
394 mass, positions, and desired speeds of different individuals are randomly distributed.  
395 To avoid chance in a single experiment, the simulation is repeated 100 times for each  
396 case in this study.

### 397 **Effects of different competitive degree on evacuation**

398 Fig. 9 presents the results of 100 simulations with varying proportions of  
399 competitive people when the inclined angle  $\theta$  is  $0^\circ$ . The simulations demonstrate strong  
400 robustness and an even distribution of results. Comparing the average evacuation time  
401 for each scenario, it can be concluded that competitive people have a positive effect on  
402 total evacuation time. As the proportion of competitive people increases, the total  
403 evacuation time tends to decrease. This finding is consistent with the previous study  
404 (Cao et al., 2021). However, in this study, the competitive degree is determined by two  
405 factors: the inclined angle and the crowd density in the perception area. As a result, the  
406 competitive degree is small when  $\theta = 0^\circ$ , leading to a relatively slow trend in the total

407 evacuation time in Fig. 9 with no significant difference.

408 Fig. 10 shows that the evacuation paths of different proportions of competitive  
409 people tend to be curved and jittery near the exit. This is mainly due to congestion  
410 caused by a large number of people gathering at the exit after the evacuation has started.  
411 Even though competitive people have a higher desired speed at this point, congestion  
412 still restricts the overall evacuation process. In contrast to von Schantz and Ehtamo  
413 (2019), this study did not observe significant stratification between competitive and  
414 normal people. This is because at the beginning of the evacuation phase, people are  
415 more dispersed, resulting in a lower degree of competition among competitive people  
416 and similar evacuation trajectories between competitive and normal people. However,  
417 as a large number of people gather at the exit, both competitive and normal people are  
418 subject to greater congestion, resulting in greater inter-crowd forces and desired forces  
419 for all pedestrians. At this point, all individuals have an urgent desire to evacuate from  
420 the room, making it impossible to observe a clear stratification phenomenon.

421 In Fig. 11, this model is compared to study (von Schantz and Ehtamo, 2019) of  
422 flow rates at exits. The results show that von Schantz's study reaches its maximum at a  
423 competitive proportion of 0.25, while this model reaches its maximum at a competitive  
424 proportion of 0.5. This difference is primarily due to the fact that the competitive  
425 behaviour identified in this model changes in real-time, resulting in a delayed and  
426 varying degree of competition, which is more in line with reality where individuals  
427 cannot always remain competitive. Additionally, the exit width in this paper is 1m  
428 compared to von Schantz's exit width of 1.2m, resulting in a lower overall exit flow  
429 rate. However, when comparing Fig. 9, it can be seen that although the flow rate at the  
430 exit reaches its maximum at a competitive proportion of 0.5, the total evacuation time  
431 is still the smallest at a competitive proportion of 0.9. This may be because Fig. 11  
432 calculates the average flow rate at the exit, and when the proportion of competitive  
433 people is 0.5, although the escape speed of this part of the crowd increases, the arch  
434 formed at the exit lasts for a longer period of time, resulting in an increase in the exit  
435 flow rate without reducing the total evacuation time (Sticco et al., 2022).

436 In order to describe the evacuation process at the exit in more detail, Fig. 12 plots

437 the empirical survival function of pedestrians in log-log axes. The statistic is the  
438 probability that the time interval  $\Delta T$  between two consecutive people passing through  
439 an exit is greater than  $\delta t$ . In Fig. 12, when a point's x-coordinate is  $10^0$  and its y-  
440 coordinate is  $10^{-1}$ , it indicates that the probability of the time difference between two  
441 consecutive people passing through the exit exceeding  $10^0$  s is  $10^{-1}$ . Furthermore, the  
442 probability of  $\Delta T$  being greater than 0.1 s is 1 for all three scenarios with  $\alpha = 0.1, 0.5,$   
443 and 0.9, as shown in Fig. 12, this suggesting that in all of these scenarios, the  $\Delta T$  is  
444 greater than 0.1 s. It is noteworthy that in this model, an increase in the proportion of  
445 competitive people tends to reduce the likelihood of longer  $\Delta T$  intervals. However, the  
446 opposite phenomenon is observed in the study (Hidalgo et al., 2017), i.e., increasing  
447 the desired speed leads to longer congestion, this is due to the incorporation of a real-  
448 time system for assessing the competitive degree in this model. The competitive degree  
449 depends on density in the perception area, but the competitive people may not always  
450 remain in a fully competitive state. And, with the density of people in the perception  
451 area increasing, the desired speed of competitive people increases, and thus a longer  $\Delta T$   
452 is less likely to occur, which is why the "fast is slow" phenomenon does not occur  
453 (Garcimartín et al., 2016). However, it is worth noting that the probability of  
454 simulations obtaining  $\Delta T > \delta t$  remains of the same order of magnitude as the results of  
455 real experiments (Feliciani et al., 2020; Hidalgo et al., 2017).

### 456 **Effects of competitiveness on different inclination angle**

457 In the event of a ship's inclination due to water ingress, passengers on board can  
458 quickly perceive that they are in an uneven space, which can cause panic to those inside  
459 the cabins. Panic tends to intensify as the inclined angle increases (Wang et al., 2020).  
460 Fig. 13 illustrates the total evacuation time when the proportion of competitive people  
461 increases from 0.1 to 0.9 in different inclination scenarios. It can be observed that when  
462 the ship is inclined at a certain angle, the total evacuation time tends to decrease as the  
463 proportion of competitive people increases. When  $\theta = 25^\circ$ , the total evacuation time  
464 decreases by 38.44s when the proportion of competitive people increases from 0.1 to  
465 0.9, while it only decreases by 16.02s when there is no inclination. It is worth noting

466 that although there is a significant difference in the reduction of total evacuation time,  
467 the reduction is stable in the range of 18.45%-22.71% in corresponding scenarios.  
468 Additionally, when  $\theta \leq 10^\circ$ , the total evacuation time decreases the fastest when  $\alpha$  is 0.5.  
469 The reason for this is that the flow rate at the exit reaches its maximum at this point,  
470 effectively improving overall evacuation efficiency, which is consistent with results  
471 obtained in Fig. 11. However, when  $\theta > 10^\circ$ , the evacuation time decreases the fastest  
472 at  $\alpha = 0.7$  due to the reduction in movement speed of all individuals caused by the large  
473 inclined angle, and at this point, the exit flow rate does not reach its maximum at  $\alpha =$   
474 0.5. Therefore, compared with scenarios on flat ground or small angles of inclination,  
475 increasing the proportion of competitive people can effectively promote overall  
476 evacuation efficiency and process in appropriate situations.

477 Similar to the description above, the survival function of people can visualize the  
478 efficiency of different evacuation scenarios. Fig. 14 illustrates the exponential  
479 distribution of the probability of  $\Delta T > \delta t$  for different inclination angles for  $\alpha = 0.5$ ,  
480 which displays congestion at the exits in various scenarios. Higher congestion resulting  
481 in a higher probability that  $\Delta T$  becomes longer indicates that congestion at the exits  
482 lasts for a longer period of time (Fang et al., 2022). It is worth noting that when the  
483 survival function at  $\theta = 25^\circ$  is further away from the other two curves, which means that  
484 the greater the amount of attenuation of walking speed, the longer the duration of crowd  
485 congestion. Congestion frequently occurs during evacuation as bottleneck areas cause  
486 people to gather faster than the evacuation capacity of the exits. When the entire crowd  
487 is observed, external pressure (disaster or danger) compresses the crowd continuously  
488 in bottleneck areas, causing individuals' distance to become smaller and smaller. At this  
489 point, it is easy for the number of people at the exit to reach equilibrium and form an  
490 arch, and the duration of this phenomenon has a direct impact on congestion time and  
491 a negative impact on evacuation outcomes (Li et al., 2019). As the angle of inclination  
492 increases, people require more energy and time to adapt to the environment and adjust  
493 their body state accordingly, making them less capable of breaking the arch equilibrium,  
494 resulting in a greater probability that  $\Delta T$  becomes longer.

## 495 **Discussion**

496 In terms of crowd emergency management, maintaining a certain social distance  
497 between individuals is crucial during normal scenarios, which is reflected by the inter-  
498 peer force  $f_{ij}$  in the basic social force model. However, in the presence of danger,  
499 panicked individuals may exhibit a shortening of social distance and may even push  
500 and crowd with others, which is a phenomenon that has received significant attention  
501 both in real-life situations and modelling simulations (Andrés-Thió et al., 2021).

502 Through the simulation analysis, it becomes evident that increasing the proportion  
503 of competitive individuals can lead to a reduction in the total evacuation time. However,  
504 it is worth noting that when the parameter  $\alpha$  reaches 0.5, the evacuation time might  
505 experience its most significant decrease. Further statistical analysis of the simulation  
506 results reveals that a higher  $\alpha$  is more likely to disrupt the equilibrium at the exit,  
507 potentially causing congestion. In inclined scenarios, increasing  $\alpha$  can indeed accelerate  
508 the evacuation process to a certain extent. However, individuals in such scenarios must  
509 expend more effort and time to navigate the challenges posed by the inclined ship's  
510 impact on their movement. Consequently, despite heightened competitive desires  
511 compared to scenarios without an inclination angle, the total evacuation time may not  
512 be effectively shortened.

513 Based on the simulation results of the proposed model in this study, it is believed  
514 that including a reasonable number of competitive people is beneficial to the overall  
515 efficiency and evacuation results of human evacuation from ships. From the perspective  
516 of crowd management, more attention should be paid to individuals in congested areas  
517 during the evacuation process. Under the premise of ensuring safety, appropriately  
518 increasing the proportion of competitive people can improve the flow rate at the exit.  
519 Additionally, the impact of ship inclination on human movement should be fully  
520 considered when formulating evacuation strategies. The crew should be arranged to  
521 organize and guide the evacuee to avoid stampedes caused by excessive panic among  
522 individuals.

## 523 **Conclusion**

524 This study proposes a social force evacuation model nested with a real-time  
525 competitive degree assessment system to study human competitive behaviour in  
526 evacuation scenarios of inclined ships. In addition to considering the effect of ship  
527 inclination on human movement, the model redefines the perceived area of competitive  
528 people in the evacuation process and calculates the competitive degree in real-time at  
529 each time step using crowd density and inclined angle as input parameters. To provide  
530 a more detailed description of the human evacuation process in an inclined ship, the  
531 effect of different inclination angles and the proportion of competitive people on the  
532 evacuation result is analysed using the dining room of a ship as a case study.

533 This study provides a comprehensive exploration of the influence of competitive  
534 behaviour on the evacuation process, taking into account the severity of the accident.  
535 Additionally, the real-time assessment system for measuring human competitiveness  
536 ensures that simulation results closely approximate real-world conditions. Through  
537 quantitative analysis of the simulation outcomes, the study identifies the factors  
538 constraining the evacuation process, thus offering valuable insights for the development  
539 of evacuation strategies on inclined ships. The findings from this research can serve as  
540 a foundation for future work on human evacuation aboard ships, ultimately enhancing  
541 the safety of passenger vessels.

542 However, this work has some limitations due to the lack of validation data. Firstly,  
543 the model only considers scenarios where the ship maintains a single inclination angle  
544 and does not fully account for the effect of changes in inclination angle on human  
545 movement. Secondly, the analysis only covers the evacuation process in a single room  
546 and not the overall evacuation process of a full-size ship. Finally, the model does not  
547 integrate competitive behaviours such as group behaviours and helping behaviours that  
548 may occur during the evacuation process. These limitations will be addressed in future  
549 work.

## 550 **Data Availability Statement**

551 All data, models, or code that support the findings of this study are available from

552 the corresponding author upon reasonable request.

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559

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686

**Table 1 Rules for assessing the competitive degree.**

No	Inclination angle	Density	Competitive
1	S	L	VW
2	S	M	W
3	S	H	M
4	M	L	W
5	M	M	M
6	M	H	S
7	L	L	M
8	L	M	S
9	L	H	VS