MODELLING ROUTE CHOICE IN CROWD EVACUATION ON PASSENGER SHIPS

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SUMMARY

This paper proposes an agent-based simulation model with route choice process to predict the crowd behaviours and evaluate the evacuation safety on passenger ships. The model focuses on the behaviours of two common types of passengers that are not typically accounted for during most evacuation analyses, namely, passengers who are not familiar with the ship layout and passengers who have family members or friends with them. In the proposed model, a marker concept is introduced to represent critical routing points of the layout and passenger agents make a route choice based on their surroundings and characteristics instead of just following the shortest routes. The simulation model is tested by two small but targeted scenarios and one comprehensive scenario on a ship deck. For ship designers, a more realistic evacuation time is provided to better assess the evacuation performance of a ship, and a heat map of crowd density is presented to identify possible bottleneck areas.

1. INTRODUCTION

As a safety issue, evacuation has always been a hot topic for maritime regulatory and industry bodies, especially when ship disasters such as the Costa Concordia disaster (2012, with 32 fatalities) happen. In 1999, the International Maritime Organization (IMO) formulated the first guideline on how to conduct evacuation analysis for ships and has been updating it as long as there are new data or new techniques. Evacuation simulation, referred by the IMO evacuation guidelines as an advanced method to conduct evacuation analysis, is widely used by the maritime industry to help ensure evacuation safety from aspects such as design, training and operation (Vassalos *et al.*, 2002). Several recent and sophisticated evacuation simulation tools for the ship environment are listed below:

- EVI (Vassalos *et al.*, 2002; Guarin *et al.*, 2014) is developed from a velocity-based model with continuous geometry. The tool is able to incorporate the hazard effects of fire and flooding. It can also model uncertainty of human attributes.
- AENEAS (Meyer-König *et al.*, 2002; Meyer-König *et al.*, 2005) is built based on a simple cellular automata model, which makes it ultra-fast when simulating the movement of thousands of agents on board.
- maritimeEXODUS (Galea *et al.*, 2003; FSEG, 2018) is developed from a rule-based model with discrete geometry. It considers the impact of heel and trim of ships on agents by incorporating experiment data. The tool is good at modelling fire effect. Moreover, some features such as dynamic motion impact, life-jacket retrieval and signage system can be modelled in the simulation.
- SIMPEV (Park *et al.*, 2015) is constructed from a simple velocity-based model with continuous geometry. It is able to demonstrate group phenomenon such as leading and following behaviour. This tool is validated by the tests specified by the IMO evacuation guidelines and full-scale evacuation datasets (Galea *et al.*, 2013) generated from the SAFEGUARD project.
- VELOS (Ginnis *et al.*, 2010; Ginnis *et al.*, 2013) is built from a velocity-based model with continuous geometry. It can show various group behaviours such as cohesion, waiting and finding. Some features such as virtual reality system, motion induced interruptions, crew assistance make this tool reproduce more realistic evacuation process.
- Balakhontceva *et al.* (2015) and Balakhontceva *et al*. (2016) proposed a tool based on an improved social force model to simulate the movement of passengers on board. The tool integrates a ship motion influence model and a wave propagation model to better show ship motion impact on agents and demonstrate the hazard effect of storms.
- Kana & Droste (2017) proposed an egress method based on Markov decision processes. They model both the distribution and the movement of the people probabilistically and are thus able to generate generalized trends of evacuation behaviour without the need to model each person individually, thus making this method well suited for early stages of ship design.

The motivation of this paper is to improve evacuation simulation by considering two passenger characteristics leading to specific behaviours that are frequently observed in the crowd evacuation on a passenger ship, but considered rarely in current simulation models: layout familiarity and social relationship. In terms of layout familiarity, most models give all agents a default attribute that they have full knowledge of the ship layout or they know where they are going at the start of the evacuation (Meyer-Komag *et al.*, 2002; Vassalos *et al.*, 2002; Galea *et al.*, 2003; Ginnis *et al.*, 2010; Park *et al.*, 2015; Balakhontceva *et al.*, 2016). With that attribute, the agents do not have to find paths, instead they basically follow the shortest evacuation routes or walk along assigned routes while in actual situations these routes may be interrupted and re-planned because of a hazard, a counter-flow, or a group leader. When it comes to social relationship, current ship evacuation models mainly care about the cohere/group behaviour which keeps together agents that are geometrically close to each other (Galea *et al.,* 2003; Park *et al.,* 2015). VELOS (Ginnis *et al.,* 2013) presented an enhanced-cohere behaviour model to produce different levels of group behaviours, which seems to have the potential to show the behaviours of friends and family members such as finding, waiting, leading and following.

To consider the impact of layout familiarity and social relationship on passengers' routing behaviour on board, this paper incorporates a route choice model in an agent-based simulation model. Route choice models have been developed in other fields in order to represent the probability of each alternative route in a given network based on attributes and characteristics of the decision makers (refer to Bovy & Ēliyyahû (1990) for the first book on the subject). More recent route choice literature focuses on adaptive behaviour in order to take into account the stochastic and dynamic nature (e.g., Gao *et al.*, 2010). However these models have not yet been incorporated into evacuation models for ships where the route choice behaviour is a key element to measure the evacuation performance of the ship designs. Therefore, the main contribution of this paper is that a novel simulation is developed with an integrated route choice model for analysing crowd behaviour in evacuation of passenger ships.

The route choice model in this paper is based on a concept of a "marker" that represents specific locations on the layout. Each alternative route is composed of a certain number of markers. The route choice model represents the choice of each agent between their alternative routes. Layout familiarity is reflected by giving agents different initial marker maps. Social relationship can be demonstrated by adding another special marker: partner marker. By implementing the two agent characteristics in the route choice model and the agent-based simulation model, results of evacuation analysis for passenger ships can be considered to be more realistic, which is helpful for ship design and emergency arrangement.

This paper is organized as follows. Section 2 introduces how the two agent characteristics, namely layout familiarity and social relationship, are considered in this paper. Section 3 puts forward a route choice model to include the two agent characteristics in evacuation simulation. Section 4 tests the sensitivity parameter of the model and the ability of showing route choice behaviours. Section 5 demonstrates the results of computational experiments on one comprehensive scenario on a ship deck. Section 6 discusses the critical points of the proposed approach and gives concluding remarks. Section 7 gives further research directions.

2. CONSIDERED PASSENGER CHARACTERISTICS

Layout familiarity and social relationship are the two passenger characteristics this paper focuses on. This section provides evidence on why they need to be considered and the general ideas of how they are considered in the proposed models.

2.1 LAYOUT FAMILIARITY

Passengers on a large cruise ship normally have very little knowledge of the complex moving platform (Vassalos *et al.*, 2002), and thus they may not follow the pre-planned routes in the evacuation arrangement but instead may walk along arbitrary or individually preferred routes to reach assembly stations. For example, when someone not familiar with the layout comes out of their cabin, they might make a detour to the staircase which can actually be reached in a different, more direct and quick way. In fact, layout familiarity or environment familiarity has been studied in building evacuation fields since 1985 (Sime, 1985; Korhonen *et al.*, 2008; Ronchi *et al.*, 2013). Researchers observed that the characteristic leads to the affiliation behaviour that individuals tend to move toward familiar persons and places when escape occurs. However, current models considering the characteristic mainly focus on the familiarity with exits and the familiarity is only regarded as a permanent attribute of agents without considering that agents will get more familiar with new exits throughout the evacuation process.

Current research on layout familiarity-related behaviours in evacuation could provide a clue how the characteristic should be modelled. Li *et al.* (2014) analysed the data collected from a field survey conducted in a large market and found that pedestrians searched their corresponding personalized spatial cognitive road network to find some roads which maybe a route to the destination. Kinateder *et al.* (2018) observed in controlled experiments that pedestrians were more likely to exit through familiar doors than through a second available exit. Andresem *et al.* (2018) conducted a field study to investigate the route choice of people in dependency on their familiarity with an office building. They found that people who are very familiar with the spatial layout prefer to use the shortest path. Casareale *et al.* (2017) collected data through questionnaires and real footage of evacuation on a cruise ship. The familiarity effect is visible that evacuees did not proceed towards the exits on the deck they reached since they were not familiar with exit locations. Nevalainen *et al.* (2015) conducted user studies in authentic environments and found that passengers base their route choice on their own perception and spatial knowledge in passenger ships.

In this paper, the authors consider layout familiarity as layout knowledge, and assume that each agent has a mind map of the layout which is used to represent the knowledge. Naturally each agent can be given an individual initial map and the map can be expanded when a new layout is explored. In order to represent the maps, the authors introduce the marker concept. A marker indicates a specific location on the layout such as a door, an intersection or an assembly station. Thus the ship layout can be regarded as a topological network/map of markers. Agents who know all the markers on the layout can search the whole marker map in their minds and find the shortest route to assembly stations. On the other hand, agents who are only partially familiar with the layout need to expand the marker maps in their minds and find their routes to assembly stations as they move about the ship.

2.2 SOCIAL RELATIONSHIP

Passengers who live in the same cabin usually have some relationship such as friendship or kinship with each other. Passengers with those relationships will behave differently from individual passengers when evacuation happens. For example, a husband is likely to first gather his wife and then evacuate together with her if the general alarm is sounded. The behaviours and the phenomena caused by the social relationship can also be seen in pedestrian evacuation in buildings (Korhonen *et al.*, 2008; Pan, 2006; Qiu & Hu, 2010). However, researchers mainly focus on the interaction for large groups of people instead of small groups of people which have stronger connections and specific behaviours such as kin behaviours (Yang *et al.*, 2005).

Experiments and questionnaires have been carried out to study the behaviours of small groups in evacuation. Ma *et al.* (2017) conducted evacuation experiments in an 11-storey office building and investigated the cooperative and competitive behaviour characteristics of different types of small groups. Haghani *et al.* (2019) reported a lab-in-the-field evacuation experiment to investigate group behaviours. In the experiment, the exit-choice mechanism of groups showed a great degree of similarity to that of single individuals. Li *et al.* (2020) carried out building evacuation experiments to study the social relation and group behaviour in evacuation. They found that the crowd forms different small groups in evacuation and the social relation affects the leader-and-follower behaviour. Wang *et al.* (2020) examined the behaviours of passengers on a ship by a questionnaire survey. The survey showed that passengers on board are more likely to return to the cabin when their families are left behind.

To study the characteristic of social relationship on board, this paper focuses on small groups with two members, which are connected by the same identification. The evacuation process for small groups is divided into two stages (Korhonen *et al.*, 2008): the gathering stage and the egress stage. In the first stage, a role type, either **finder** or **waiting**, is assigned to each member of a group to indicate the group role of the member. A finder is supposed to find their partner actively as long as the finder is able to do that with their layout knowledge. A waiting person is supposed to wait for their partner as long as the partner is able to find them. When they can see each other, they walk to each other. Here it is assumed that the actions of partner members are kept synchronous to make their interaction not too complex. There are three combination types: finder-finder, finder-waiting, and waiting-waiting. In the second stage, another role type, either a leader or a follower, is assigned. A leader walks to the assembly station while a follower follows the leader. There is only one combination type: leader-follower. A special marker, **partner marker**, is created to include the interaction of group members in their two-stage evacuation process.

3. ROUTE CHOICE MODELLING IN EVACUATION

The behaviours of the passenger agents with the characteristics of layout familiarity and social relationship are demonstrated in the simulation by modelling their unique route choice process.

3.1 DEFINITION OF ROUTE

The definition of route is based on the marker concept introduced in Section 1 and Section 2.1. The authors define 6 basic markers in this paper:

- **Goal**, the assembly station
- **Cross**, the intersection point leading to different directions.
- **Outdoor**, the outside of a door.
- **Indoor**, the inside of a door, only connecting with one outdoor marker.
- **Partner**, the partner of an agent, existing only between partners.
- **Self**, an agent himself/herself, existing only for the agent.

Any two markers should be connected as long as the line connecting them is not obstructed by walls (note that the connection rule for the indoor marker is special). For each agent, the alternative routes are found by searching their own marker map in mind. Each alternative is composed of a certain number of markers, which lead the agent from their current location (self marker) to the last marker of the alternative. The authors call the last marker of each alternative as a “go-for marker”, which represents the marker that an agent is likely to choose as a temporary destination. There are three types of go-for markers:

- The first type includes goal markers, namely the markers representing assembly stations, which is obvious.
- The second type includes not fully explored cross markers or outdoor markers. For agents with partial initial layout knowledge not covering an assembly station, they have the desire to expand their marker maps and find assembly stations.

- The third type includes partner markers. For agents having partners with them, they will consider their partners as temporary destinations.

3.2 ROUTE CHOICE MODEL

Let $n \in N$ represent the agents. For each agent n, the choice set is represented by I_n. The choice among those alternatives will be probabilistic based on their route attributes and personal characteristics. The probability of choosing alternative i for individual n based on a logit model is given as follows:

$$P_{in} = \frac{\exp(V_{in})}{\sum_{j \in I_n} \exp(V_{jn})} \quad (1)$$

where

- V_{in} is the systematic utility of alternative i for agent n. Note that the random utility is given by $U_{in} = V_{in} + \varepsilon_{in}$ where ε_{in} is the random term which is assumed to follow extreme value distribution. Systematic utility, V_{in}, is represented by observed variables and ε_{in} is unobserved that leads to the probabilistic choice behaviour.

Assume that agents evaluate the utility of an alternative by the total time duration to get to an assembly station by choosing this alternative. The total time duration is composed of three parts: the travel time T along the alternative, the delay D caused by crowd, and the estimated travel time E from the end of the alternative to an assembly station, which are calculated by Equation (2)-(4) respectively.

$$T_{in} = \frac{L_{in}}{v_{in}} \quad (2)$$

where

- L_{in} represents the distance from the current position (self marker) of agent n to the end (go-for marker) of alternative i for agent n.
- v_{in} is the speed that agent n would try to maintain during evacuation.

$$D_{in} = \frac{C_{in}}{f w_{in}} \quad (3)$$

where

- C_{in} represents the number of agents heading to the same location, namely the go-for marker of alternative i, with agent n.
- f is the specific flow, which represents the number of agents passing a route per unit time per unit of clear width (IMO, 2016). In this paper it is set to be a constant value, 1.3 p/m/s (person/meter/second).
- w_{in} is the minimum width of alternative i for agent n.

$$E_{in} = \frac{A_{in} M_{in} L_n}{v_{in}} \quad (4)$$

where

- A_{in} represents the impact of crowd C_{in} on the estimated time. The authors formulate this parameter because of the herding phenomenon and the thought that crowd could indicate a closer safe area. In this paper, A_{in} is set to be 2 when $C_{in} = 0$, 1.5 when $C_{in} = 1$, $1 + (C_{in} - 50)^2 / (1-50)^2 / 2$ when $1 < C_{in} < 50$, 1 when $C_{in} \geq 50$. Therefore, there is a big difference between the estimated distances for $C_{in} = 0$ and $C_{in} = 1$, and when C_{in} is large enough, the effect of larger C_{in} indicating a closer safe area should disappear.
- M_{in} represents the impact of the go-for marker on the estimated time. This parameter is formulated because different go-for markers can indicate a safe area with different distances. For example, goal marker indicates zero distance, and cross marker indicates a closer safe area than outdoor marker. In this paper, M_{in} is set to be 0 when the go-for marker is the type of goal, 1 when it is a cross marker, 2 when it is an outdoor marker. The values could lead to the following order of preference for go-for markers: goal > cross > outdoor.
- L_n is the maximum value of L_{in} for agent n, namely the one with the longest distance among the current alternatives. This value is chosen as a common reference when calculating estimated time of different alternatives for an agent. Here the value of L_n is conservative to ensure that the total distance $A_{in} M_{in} L_n$ to an unknown goal marker should be longer than that to a known goal marker.

Based on above attributes, the authors define the utility function as follows:

$$V_{in} = \alpha (T_{in} + D_{in} + E_{in}) \quad (5)$$

where

- α is the sensitivity to the total time duration, i.e., the impact of the duration on the utility. Here it should be noted that α is a parameter with negative value as the duration has negative impact on the utility. α could vary across different time attributes T_{in}, D_{in}, E_{in} in order to represent different sensitivities towards each of them (See Appendix A, the route choice model with different sensitivities is compared with experimental data). However, here the authors opted to represent these differences with parameters within each term as described above.

3.3 ROUTE CHOICE MODEL AND EVACUATION SIMULATION MODEL

The route choice model is encoded in an agent-based simulation model, which is part of an open-source pedestrian simulation tool SteerSuite (Singh *et al.*, 2014). See Appendix B for a brief introduction of the tool and how this paper uses it. See Appendix C for validating the simulation model by the 12 tests specified in the IMO evacuation guidelines (IMO, 2016). The process of evacuation simulation and route choice is shown in Figure 1. It can be seen that agents do not have to make a route choice in every time step; instead, they decide whether to do that according to their updated marker maps and current movement condition. For example, a person who is going to a not-fully-explored/known intersection point will reconsider their route choice decision only when a new intersection point or a new assembly station (i.e., a new go-for marker, which will be identified from the updated marker maps) is encountered. Besides the trigger of changing go-for markers, agents will also reconsider their decisions if they do not move forward much for a certain period, which means they get stuck and the current route is too crowded or not available.

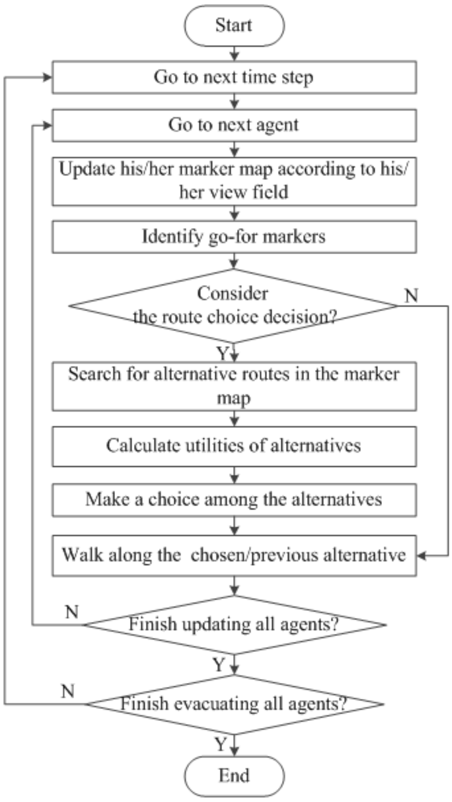


Figure 1: The flow chart of evacuation simulation and route choice

4. PARAMETER TEST AND FUNCTION TEST

The parameter test is used to calibrate the sensitivity parameter α , and the function test is used to show whether the models are able to demonstrate the behaviours caused by characteristics of layout familiarity and social relationship.

4.1 SENSITIVITY ANALYSIS FOR ALPHA

A simple scenario, as shown in Figure 2, is introduced to analyse the effect of parameter α on route choice. There is a symmetrical layout. Two bunches of people with full layout knowledge are in the left and right, and a single person without layout knowledge is in the middle. No group is assigned. The number of people in the right bunch is 10, which is fixed. When changing the number of people in the left bunch, the probability of the middle person's choosing left direction should keep changing.

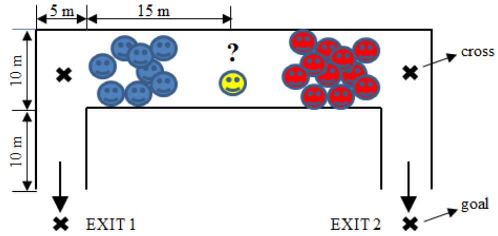


Figure 2: A symmetrical corridor scenario to test the sensitivity parameter

Different values of parameter α are set to observe the different relations between crowd and probability, as shown in Figure 3. All five curves have the same trend: when the number of people in the left bunch increases from 0 to 1, the probability of choosing left has a sharp increase, which is caused by the discontinuous change of parameter A_{in} ; when the number increases from 1 to about 23, the probability increases to a maximum value because more people indicate a closer exit; after that, the probability experiences a decrease due to the delay caused by crowding. It can be seen that higher values lead to more sensitivity of probability to crowd size. In the following experiments a middle value 0.5 is set for parameter α .

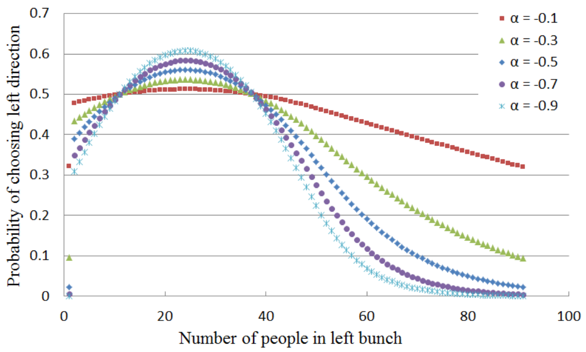


Figure 3: Sensitivity analysis of parameter α on route choice as crowd size changes

4.2 TEST OF THE TWO CHARACTERISTICS

4.2 (a) A Maze Scenario: Increasing Familiarity versus Full-Familiarity

A maze scenario with the size of 42m×36m is depicted, as shown in Figure 4, to compare the different behaviour patterns of a passenger with no layout knowledge and a person with full knowledge when facing complex layout. There is only one passenger at the entrance, and they should go to the exit finally. If the passenger is familiar with the layout, they are expected to just walk along a single route to the exit without detour. However, if the passenger does not know the layout at all, they are expected to find ways to the exit and possibly experience some detours.

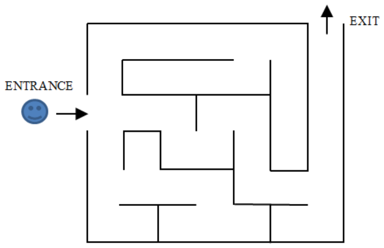


Figure 4: A maze scenario to show familiarity-related behaviours

Here 100 simulations are carried out for each of the two cases. The tracks in the two cases are shown in Figure 5. It is can be seen that in their 100 simulations the case of full familiarity has only one track while the case of increasing familiarity produces many different tracks, some of which have detours because of the agent's behaviour of finding routes to the exit, which is consistent with above expectation. The average arrival time of the agent for the case of increasing familiarity (91.12 seconds) is 59.30% longer than that for the case of full familiarity (57.20 seconds).

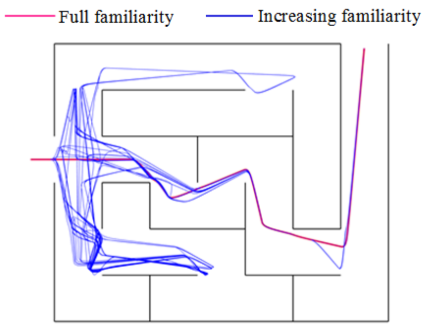


Figure 5: Comparison of tracks of agents with increasing familiarity and full familiarity

4.2 (b) A Three-Room Scenario: Small Groups Versus Individuals

A three-room scenario with the size of 45m×30m is developed, as shown in Figure 6, to demonstrate how a population with small groups behaves differently compared to a population with only individuals. There are two exits and 12 passengers who are located randomly in the layout at the start of the simulation. For the case of individuals, half of the agents are with full layout knowledge and another half with no knowledge. For the case of groups, there are 6 small groups with the size of 2 passengers, among which 3 groups are with full layout knowledge and the other 3 groups with no knowledge. The role type combinations for each of the 3 groups are finder-finder, finder-waiting, and waiting-waiting. The case of groups is expected to have a longer average clearance time than the case of individuals because group members may need to spend time to find each other.

Here 500 simulations are carried out for each of the two cases. The clearance time distributions for the two cases

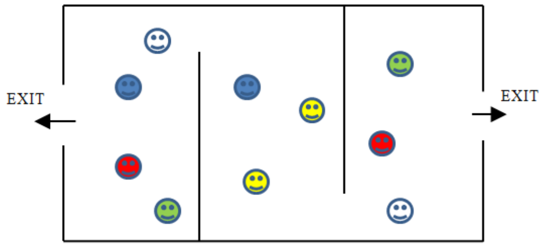


Figure 6: A three-room scenario to show behaviours of small groups

are shown in Figure 7. It is obvious that the two distributions are quite different. For the case of individuals, nearly 95% of the simulations (478) only take 20-36 seconds to evacuate all the agents, and the clearance time for more than 60% of the simulations (315) falls in the single range of 24-28. However, for the case of small groups, the clearance time for more than 95% of the simulations (482) falls in the multiple ranges from 28 to 60 approximately evenly. The average clearance time for the case of small groups is 43.74 seconds, 67.14% more than that for the case of individuals (26.17 seconds), which is consistent with above expectation.

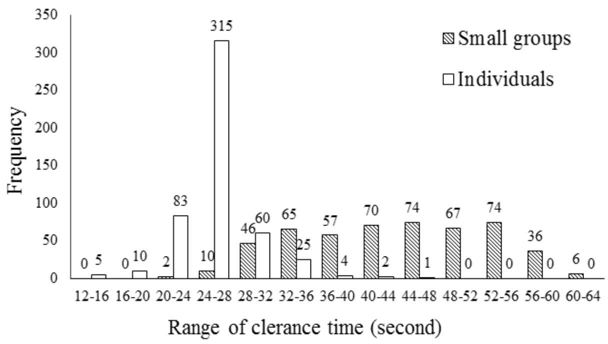


Figure 7: Comparison of clearance time distributions with small groups and individuals

5. CASE STUDY ON A SHIP SCENARIO

To test the simulation model in a real ship evacuation scenario, this paper conducts the evacuation in a cruise ship deck, as shown in Figure 8. The scenario is created based on the data set of the SAFEGUARD project carried out by Galea *et al.* (2012). The deck is the 4th deck of a cruise ship. In the data set there are 283 passengers (see dots in Figure 8) on the 4th deck, among which 197 are located in the aft restaurant area and the remain 86 in other areas. The assembly stations can be arrived at by 3 stairs (see circles in Figure 8). The simulated process is part of mustering process. Two cases with different configurations of passengers are considered: with characteristics and without characteristics. For the former, the characteristics of no/partial layout knowledge and small groups are given randomly to half of the total population respectively, which means 141 persons do not know the full layout and 140 persons have partners with them. For the latter, all the 283 passengers are with full knowledge and without partners. 50 simulations were run for each of the two cases. In a computer with CPU 4 GHz and RAM 8.00GB, it takes about 20 min to finish one simulation for the case with agent characteristics and about 10 min for the case without agent characteristics.

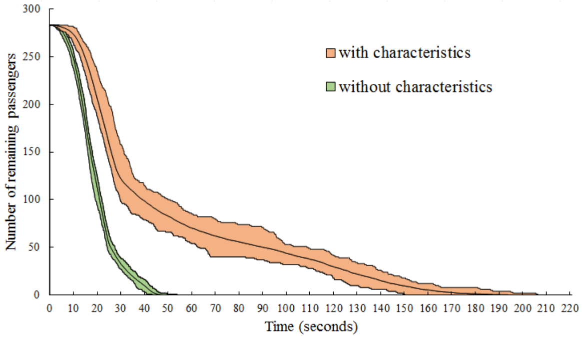


Figure 9: Comparison of evacuation curves for cases with characteristics and without characteristics

For each of the two cases, the authors depict the evacuation curves for 2 simulations from the 50 simulations which take the shortest/minimal time and the longest/maximal time to evacuate all agents, as shown in Figure 9. Besides that, the average evacuation curve of the 50 simulations is also depicted for comparison (note the simulation process for this curve does not exist as it is a synthesis of 50 simulation processes). Thus there are three curves for each case. The curves for the two cases imply two significantly different evacuation processes. After a short warm-up period, the numbers of evacuated persons increase quickly for both of the two cases, which can be called a quick-evacuation period. However, the case without characteristics evacuate more than 90% of total passengers during its quick-evacuation period (5s-30s) while the other case only evacuate about 50% during its period (10s-30s). After that, the case without characteristics finishes the evacuation during 43s-54s; the case with characteristics experiences a long slow-evacuation period and finally evacuates all passengers during 150s-206s. The reason for that difference can be found by observing the simulated evacuation processes for the two cases: after the quick-evacuation period, a few agents who are far away from stairs get to their destinations without too much congestion for the case without characteristics. However, for the case with characteristics, congestion happens frequently because of counter flow when approximately half of agents struggle to pass the narrow corridors in the cabin areas to get their partners or to find their routes.

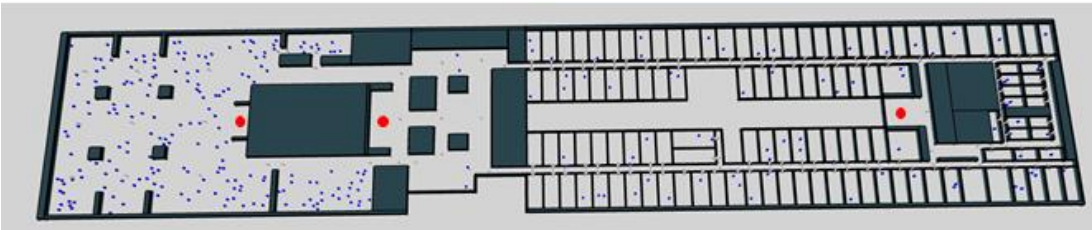
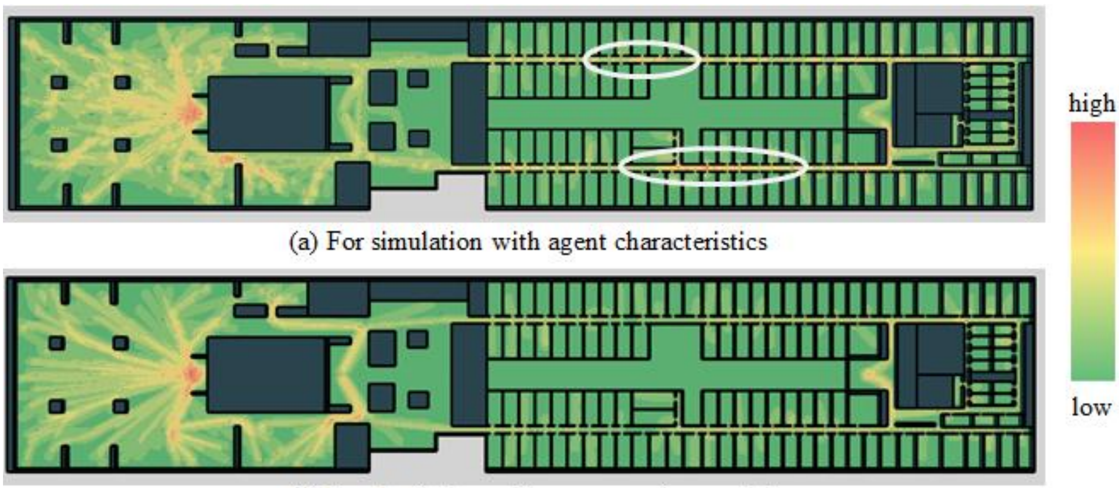


Figure 8: A comprehensive scenario of a cruise ship deck (dots represent passengers and circles represent stairs or exits)



(a) For simulation with agent characteristics

(b) For simulation without agent characteristics

Figure 10: The heat maps of crowd density for the case with characteristics and without characteristics

To identify the potential bottlenecks on a deck intuitively, heat maps of crowd density for the two cases are shown in Figure 10. The colour in any point shows the maximal value of the crowd density in the whole evacuation process for the point within an area of 1 square meters. It can be seen that besides the stair area in the restaurant (there are about 70% passengers at the start of evacuation), for the case with characteristics the two corridors in cabin areas show high density of passengers (highlighted by white circles); on the contrary, for the case without characteristics, no high density is observed in the two corridors, which are consistent with the observation of evacuation processes.

6. DISCUSSION

The authors believe that in ship evacuation, passenger characteristics such as layout familiarity and social relationship influence evacuation results significantly. An agent-based simulation model is developed to simulate the movement of passengers while a route choice model for the agents/passengers is proposed to consider the influences caused by passenger characteristics.

The characteristic of layout familiarity is interpreted as the passengers' knowledge with the layout and the corresponding behaviours are to expand mind maps and to find routes when knowledge about the safe areas is missing. Although the behaviours caused by the familiarity characteristic (Sime, 1985) are far more complex than finding routes according to mind maps, this paper is trying to include part of the related behaviours in the simulation firstly with the assumption that each agent is intelligent and rational without emotional actions. In fact, by implementing the mechanism of finding routes from mind maps, the behaviour of choosing a familiar exit can be observed in simulation.

The characteristic of social relationship means to look for another partner in this paper and the corresponding behaviours include finding the partner and leaving together with the partner, which even have higher priority than reaching a safe area as soon as possible for a passenger. The two-stage evacuation process and the group size of two members cannot be applied to all types of social relationships in a passenger ship, but with the approach of dealing with the characteristic, related behaviours such as waiting, finding, walking to each other, leading and following are observed in simulation.

Two simple scenarios and one comprehensive scenario have been designed to test the simulation model. Comparing to the ship evacuation simulation models without consideration of the characteristics, the proposed model produces evacuation results with expected longer average clearance time periods, which are caused by the detour and the delay due to passengers' behaviours of finding routes and their partners. The simulation results support the proof-of-concept of integrating passengers' routing behaviours in evaluating evacuation performance of passenger ships.

While this study focuses on two specific passenger characteristics and their impact on route choice, it is recognized that the evacuation on a ship is a complex process and many factors are not included in the route choice model. Fire and flooding are the principal hazards that lead to passenger evacuation (Guarin *et al.*, 2004; Galea *et al.*, 2003). They could cause unknown inaccessibility problem and influence the route choice of passengers. Domain semantic information attached with different spaces of ship environment also plays a crucial role in evacuation (Vassalos *et al.*, 2002; Guarin *et al.*, 2004). Agents may query these information (such as fire zone, destination) and then make choice when traversing through. Passengers are usually guided by exit signs, emergency plan or crew in evacuation. The guiding effect (Sheilds *et al.*, 2000; Kobes *et al.*, 2010) which is observed in building evacuation is also obvious on board. Adapting the route choice model to consider above factors would be an interesting topic for future research.

7. CONCLUSION AND FUTURE WORK

This study proposes a novel agent-based simulation approach to considering the passenger characteristics of layout familiarity and social relationship in the evacuation process on board. The simulation experiments in various scenarios demonstrate the route choice behaviours caused by the two characteristics. It is concluded that the proposed approach provides more accurate evacuation performance metrics for passenger ships with the consideration of the characteristics.

There are several future research directions that could be explored as follow up. First, the mass data collection with passenger characteristics and evacuation arrangement on board is an immediate direction for the purpose of further validation. Current developing techniques such as Virtual Reality are being used in studying evacuation (Sharma *et al.*, 2015; Arias *et al.*, 2020; Bourhim *et al.*, 2020), which could facilitate data collection. Second, the marker concept can be developed to include more complicated route choice behaviours of passengers. Finally, more complex scenarios with large population with more detailed heterogeneous behaviours could be simulated to test the model.

8. ACKNOWLEDGEMENTS

The research is under the support of the Project of 130, 000 GRT Large Cruise Ship Engineering Development ([2017] No. 614), Ministry of Industry and Information Technology, China. The authors acknowledge Singh *et al.* (2014) for sharing SteerSuite online, which is a useful open-source tool of developing and evaluating agent steering AI behaviours.

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APPENDIX A COMPARING WITH EXPERIMENT DATA

This appendix is to compare the proposed route choice model in the paper with experiment data. The data are from the following reference:

Liao Weichen, Kemloh Wagoum Armel U. and Bode Nikolai W. F. 2017. Route choice in pedestrians: determinants for initial choices and revising decisions. J. R. Soc. Interface.14: 20160684.
https://royalsocietypublishing.org/doi/10.1098/rsif.2016.0684

A1 EXPERIMENTAL SET-UP

Liao et al. conducted the experiments at the Dusseldorf trade fair centre (Germany) in June 2013 with a total of 138 participants (54 female and 84 male). The average

age was 24 (youngest 18 and oldest 62). These participants completed experiments for 3 different route/exit choice scenarios, as shown in Figure A1, which is from the reference. The experimental scenarios A, B, and C represent (a), (b) and (c) in Figure A1. In total, 19 experimental runs were conducted: 10 runs for A, 6 runs for B, and 3 runs for C. The runs with same initial conditions (number/distribution of persons and width of exits) were: A_1 ~ A_2 (N = 18 persons), A_3 ~ A_8 (N = 40 persons), A_9 ~ A_10 (N = 138 persons), B_1 (N = 11), B_2 ~ B_4 (N = 40 persons), B_5 ~ B_6 (N = 138 persons), C_1 ~ C_2 (N = 69 persons), C_3 (N = 138). In the following context, the above 8 experiment scenarios are represented by A (N = 18), A (N = 40), A (N = 138), B (N = 11), B (N = 40), B (N = 138), C (N = 69), C (N = 138). Refer to the Liao et al.'s paper for a detailed set-up of the experiments. The experiments were recorded by cameras. Experimental data (trajectories, egress time, exit usage, path re-planning behaviour) were extracted/identified from the video recordings.

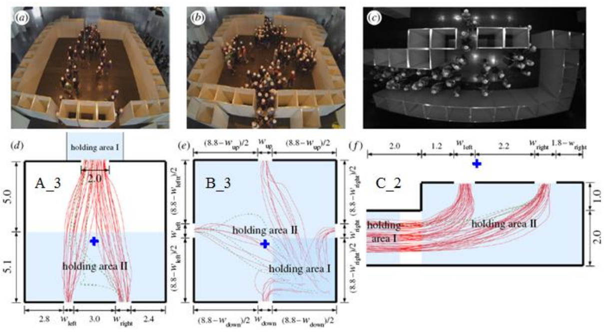

Figure A1: Liao et al. (2016) 's experimental set-up and trajectories of 3 experiments

A2 SIMULATION AND VALIDATION

We carried out simulations for the 8 experiment scenarios with different initial conditions. To do the sensitivity analysis and calibrate our model, we considered different values of the sensitivity parameters in the utility function of the route choice model. The parameters are α_T for the term of travel time and α_C for the term of delay by crowd (another term of estimated travel time would be zero in these scenarios). Higher value of α_T implies that the agent is sensitive to the time they travel to the exit. Higher value of α_C indicates that the agent will be influenced substantially by the queuing time near the exit. For each scenario, we ran 10 replicate simulations for all possible combinations of the following parameter values: α_T (0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0), α_C (0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0). It resulted in a total of 11×11×10=1210 simulations for each of the 8 scenarios. A quantitative way was required to compare the data of simulation and experiment. We used the distance measure defined by Liao et al. (2016), dist, which could capture the average differences between experiments and simulation in the number of pedestrians who used each exit and who changed their route choice.

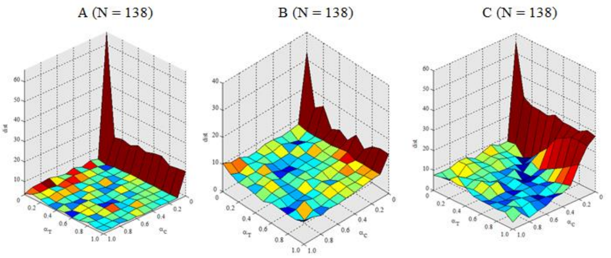

Figure A2: Sensitivity analysis based on the quantity dist for 3 experiment scenarios

The result of the sensitivity analysis for 3 experiment scenarios with 138 agents is shown in Figure A2. It could be seen that when $\alpha_C = 0$ (the term of delay is not considered), the simulations produced substantial variation with experiment data in dist for all the 3 scenarios. This suggests that the delay caused by the crowd plays an important role in the exit/route choice process. It could be observed that for the scenario C (N = 138), the combinations of higher values of α_C and α_T produced lower dist. There was no clear trend for scenarios A (N =138) and B (N =138), but the minimum value of dist still occurred when $\alpha_T = 0.5$ and $\alpha_C = 0.9$ (for A) and when $\alpha_T = 0.9$ and $\alpha_C = 0.9$ (for B). The parameter calibration results are shown in Table A1. For each experiment scenario, the minimal value of dist was obtained, which indicates the best combination of parameters for the single scenario. To avoid over-fitting the model, the calibration with all the experiment scenarios was also conducted, which calibrated with all 19 experimental runs. The best combination was $\alpha_T = 0.4$ and $\alpha_C = 0.7$.

Table A1: Parameter calibration for each experiment scenario and for all the scenarios

Experiment	α_T	α_C	dist
A (N = 18)	1.0	0.2	0.20
A (N = 40)	0	0.1	0.76
A (N = 138)	0.5	0.9	3.41
B (N = 11)	0.5	0.1	1.20
B (N = 40)	0	0.7	0.92
B (N = 138)	0.9	0.9	5.06
C (N = 69)	0	0.8	1.03
C (N = 138)	1.0	0.8	1.91
A + B + C	0.4	0.7	25.72

A closer look at the simulations with globally calibrated values of the parameters is shown in Figure A3 – A5. The trajectories of agents were drawn in Figure A3, where the red ones indicate agents walked directly towards one exit and the green ones indicate agents changed the route to use. Figure A4 compared our simulation model, Liao et al. (2016)'s simulation model and the experiment data by the ratio of agents who had path re-planning behaviours. Our model captured the frequency of changes in route choice well for all the experiment scenarios except A (N = 40) and B (N = 40). Figure A5 compared our model and experiment data by exit usage (exit 1 and exit 2 is the left exit and the right exit in all scenarios; exit 3 and exit 4 is the up exit and the bottom exit in scenarios B). The parameter calibration produced a good match in exit usage between calibrations and experiments. Based on these results, we suggest that the route choice model proposed in the main text could capture the route choice well in a broad range of scenarios.

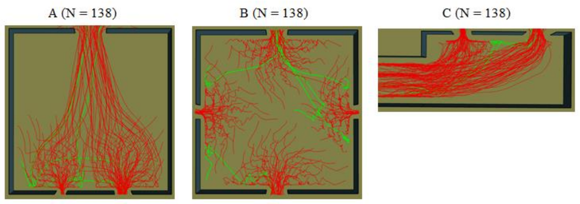

Figure A3: Examples of simulated person trajectories for scenarios A, B and C

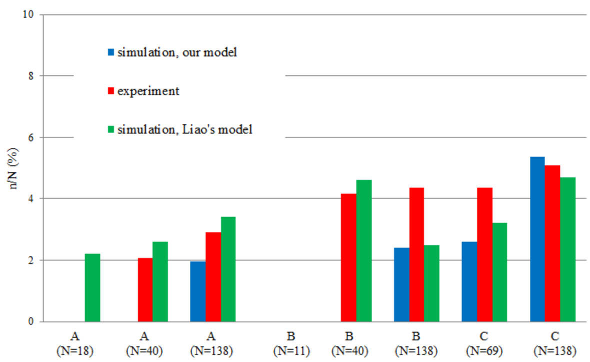

Figure A4: Comparison of occurrence frequency of path re-planning behaviours

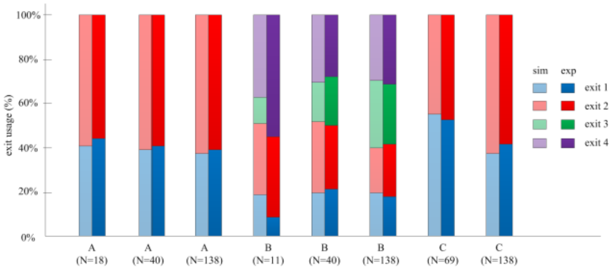

Figure A5: Comparison of exit usage

APPENDIX B THE EVACUATION MODEL AND THE MODEL SET UP

This appendix is to introduce SteerSuite, the evacuation tool we used to develop our route choice model, and the model set up for the scenarios in the paper.

B1 EVACUATION MODEL

We have developed our evacuation model based on SteerSuite (http://steersuite.eecs.yorku.ca/), which is a suite of tools, code, and test cases for developing and evaluating steering behaviours. The main components of the original SteerSuite are:

- **SteerSim:** controls simulation process and visualizes real-time simulations of steering agents.
- **Steering AIs:** provide several steering approaches such as Social Force Model and RVO2.
- **SteerBench:** benchmarks and scores simulations using a variety of benchmark techniques.
- **SteerLib:** a C++ library providing functions to help developers/researchers focus on steering AI instead of time-consuming irrelevant infrastructure.

We have revised some modules and added new functions/components to SteerSutie, including:

- **SteerSim:** The simulation engine is modified to support multiple simulation runs for a single test case.
- **Steering AIs:** The social force AI is modified for the support of the route choice model. The calculations of social forces are revised for better performance of collision avoidance.
- **Route Choice Model:** the marker concept-based route choice model, as shown in the paper.
- **SteerBench:** Original benchmarks are not used for their complexity and applicability. Instead the evacuation curve and the density map are implemented to output evacuation results.
- **SteerLib:** Functions related to ship evacuation are added, such as reading agent characteristics of layout familiarity and social relationship, implementing speeds by population demographics, supporting simple staircase simulation and so on.

B2 MODEL SET UP

There are several scenarios in the paper, including a maze scenario, a three-room scenario and a one-deck scenario. The common assumptions are that ship motion/heel/trim, hazards/fire/flooding, crew assistance are not considered, which could make the current route choice model rather more complex. As we only focus on the two characteristics of layout familiarity and social relationship, the other attributes are set to be default (travel speed 1.3 m/s, immediate response time) or not set (population demographics).

Multiple simulations were run for each scenario to get a distribution of results. The difference of the initialization for each simulation of the scenarios is as follows:

- **Maze Scenario:** only one person, with the attribute of layout familiarity; location is fixed at the entrance.
- **Three-room Scenario:** 10 persons, with both attributes of layout familiarity and social relationship; locations are randomly distributed in the three-room space for each run.
- **One-deck Scenario:** 283 persons, with both attributes of layout familiarity and social relationship; locations are randomly distributed in

several spaces (the public room, cabin areas) for each run.

APPENDIX C VALIDATION TESTS FROM THE MSC/CIRC.1 1533 GUIDELINES

We did the tests specified by the IMO MSC.1/Circ.1533 evacuation analysis guidelines, including four forms: component testing, functional verification, qualitative verification and quantitative verification (mainly the first one and the third one, 12 tests in total). It showed that the tool is able to perform as intended and produce realistic behaviours, in line with guidelines.

C1 COMPONENT TESTING

In the guidelines, there are 7 tests (TEST 1 to 7) in total to check that the various components of the tool (revised SteerSuite in this paper) perform as intended.

TEST 1: Maintaining Set Walking Speed in Corridor

Figure C1 shows the test scenario. It demonstrated that the agent covered this distance in 40 s. When the person is given a speed V, the travelling time equals to 40 m / V.

Figure C1: One person passing a corridor (2 m × 40 m) with a walking speed of 1 m/s

TEST 2: Maintaining Set Walking Speed up Staircase

Figure C2 shows the test scenario. It demonstrated that the agent covered this distance in 10 s. When the person is given an upstair speed V_u, the travelling time equals to 10 m / V_u.

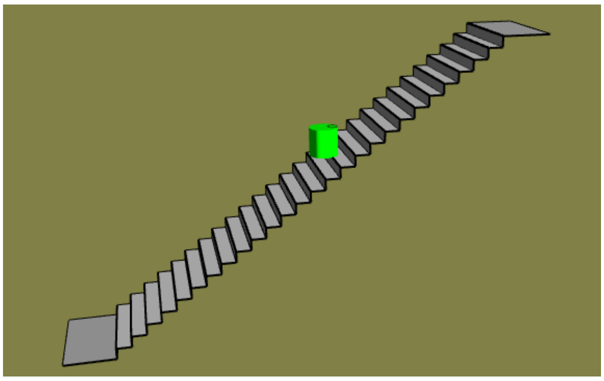

Figure C2: One person passing an incline upward (2 m × 10 m) with a walking speed of 1 m/s

TEST 3: Maintaining Set Walking Speed down Staircase

Figure C3 shows the test scenario. It demonstrated that the agent covered this distance in 10 s. When the person is given a downstair speed V_d, the travelling time equals to 10 m / V_d.

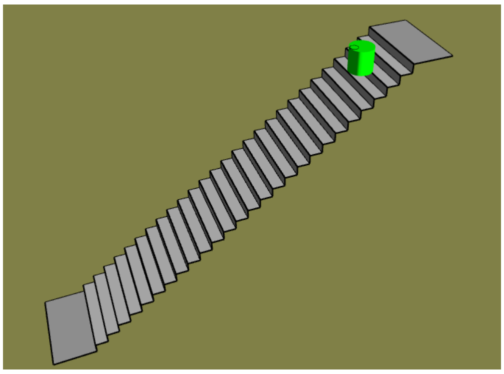

Figure C3: One person passing an incline downward (2 m × 10 m) with a walking speed of 1 m/s

TEST 4: Exit Flow Rate

Figure C4 shows the scenario. With different body size and speed settings, multiple simulations were run. The evacuation durations varied among different simulation. However, for each simulation, the flow rate over the entire period did not exceed 1.33 person / second. One of the evacuation curves is shown in Figure C5, with body sizes following a uniform distribution (0.25 m, 0.35 m) and speed being 1.3 m / s.

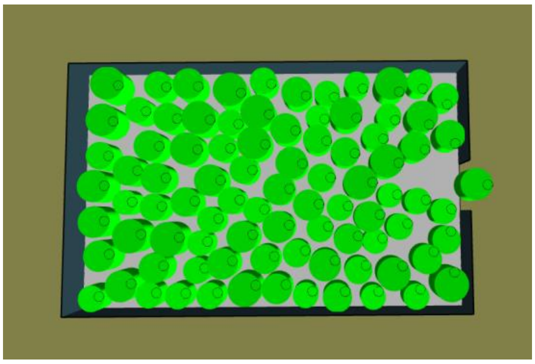

Figure C4: One hundred persons evacuating from a room (8 m × 5 m) with a 1 m exit

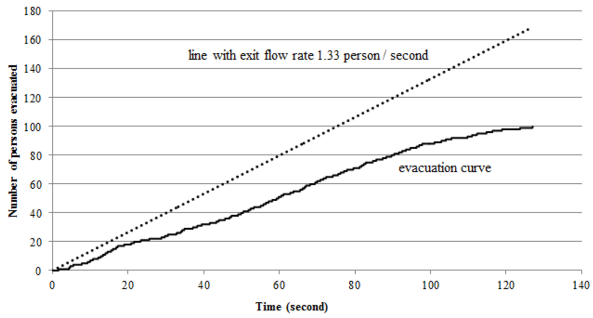

Figure C5: The evacuation curve of one simulation in TEST 4.

TEST 5: Response Duration

Figure C6 shows the scenario. 10 persons were given a response duration which follows uniform distribution between 10 s and 100 s. It could be seen that each occupant started moving at the appropriate time, namely, with a delay of response duration.

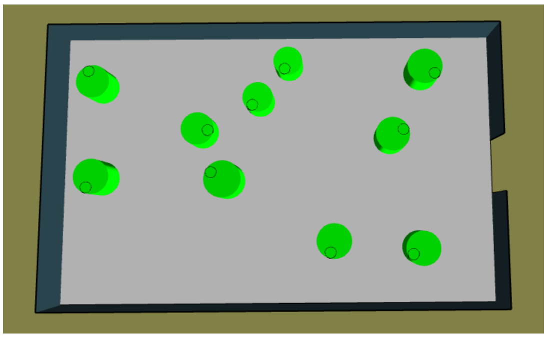

Figure C6: Ten persons evacuating from a room (8 m × 5 m) with a 1 m exit

TEST 6: Rounding Corners

Figure C7 shows the scenario. 20 persons were simulated to navigate around a left-hand corner without penetrating the boundaries.

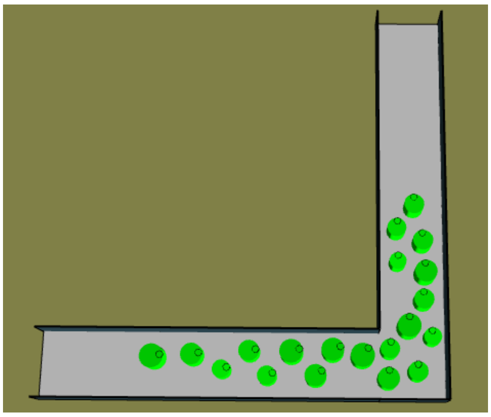

Figure C7: Twenty persons navigating round a corner

TEST 7: Assignment of Population Demographics Parameters

Figure C8 shows the scenario. 50 persons were assigned with the walking speeds specified in the guidelines. The distributions of speeds (flat terrain, stairs down, stairs up) are shown in Figure C9. It can be seen that the speeds of the 50 persons followed corresponding uniform distributions.

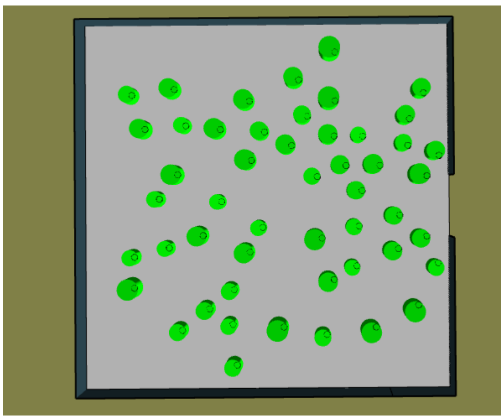

Figure C8: Fifty persons assigned with population parameters of males 30-50 years old

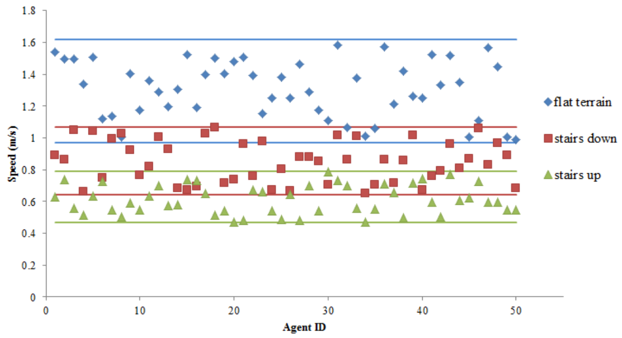

Figure C9: The speed distributions of the 50 persons in the population males 30-50 years old

C2 FUNCTIONAL VERIFICATION

The tool should be able to exhibit the ranged of capabilities to perform the intended simulations. There is no specific test in the guidelines. Refer to following websites for the model capabilities:
http://steersuite.eecs.yorku.ca/UserGuide/introduction.html
https://github.com/SteerSuite/SteerLite/blob/master/README.md

C3 QUALITATIVE VERIFICATION

This form of verification concerns the nature of predicted human behaviour with informed expectations. In the guidelines, there are 5 tests (TEST 8 to 12) in total to demonstrate the behavioural capabilities of the tool.

TEST 8: Counter Flow – Two Rooms Connected Via a Corridor

Figure C10 shows the scenario. Two rooms (10 m × 10 m) are connected via a corridor (10 m × 2 m). 100 persons will move from the left room to the right. There are 4 conditions for the right room: 0 persons, 10 persons, 50 persons, and 100 persons. They move from right to left. Both rooms move off simultaneously and the duration for the last person in the left room to enter the right room is recorded. 10 simulations were run for each condition. The result is shown in Figure C11. It is in line with the expected result that the recorded duration increases with the number of persons in counterflow increases.

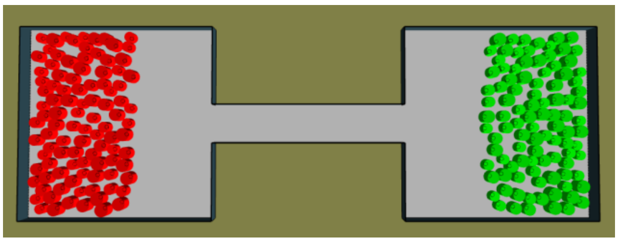

Figure C10: 100 persons from left to right (red) and 100 persons from right to left (green)

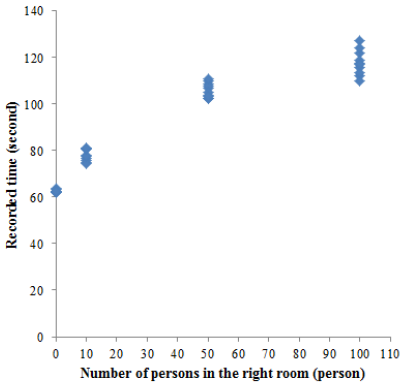

Figure C11: The recorded time for simulations of 4 conterflow numbers

TEST 9: Exit Flow: Crowd Dissipation from A Large Public Room

Figure C12 shows the scenario. 1000 persons are uniformly distributed in large rooms (30 m × 30 m). Two cases should be simulated: 2 exits and 4 exits. 10 simulations were run for each case. The clearance time was recorded, as shown in Figure C13. The average clearance time (1144.54s) of the case with 2 exits is 1.94 times of that (590.34s) of the case with 4 exits, namely, an approximate doubling, which is in line with the expected result of the guidelines.

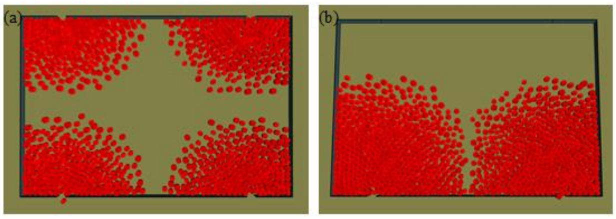

Figure C12: 1000 persons evacuating from a large public room with 4 exits (a) and 2 exits (b)

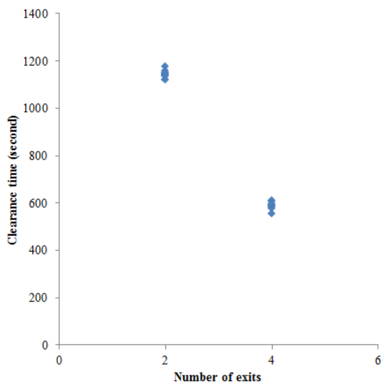

Figure C13: The clearance time for the evacuation with 2 exits and 4 exits

TEST 10: Exit Route Allocation

Figure C14 shows the scenario. In the test, 23 persons in total are allocated the main exit (the upper one, for 15 persons in the left 8 cabins) and the secondary exit (the right one, for 8 persons in the right 4 cabins). The Figure C15 shows that the simulation got the expected result that the allocated passengers move to the appropriate exits.

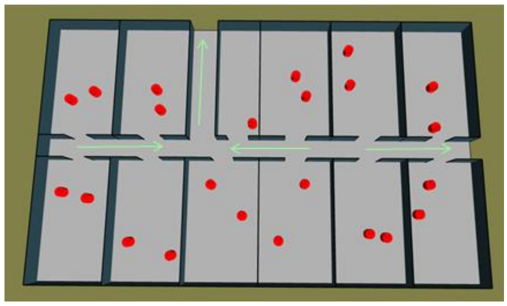

Figure C14: The cabin corridor scenario for exit route allocation test

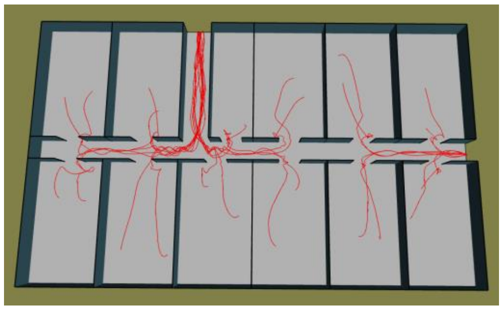

Figure C15: The tracks of the persons from initial positions to their destinations

TEST 11: Staircase

Figure C16 (a) shows the scenario. 150 persons are initially located in a room (5 m × 8 m) and are walking to the stairs up by a corridor (2 m × 12 m). As shown in Figure C16 (b), congestion appeared at the exit from the room, which produced a steady flow in the corridor. Then congestion appeared again at the base of the stairs, which is caused by that the speed on the stair is slower than the speed on the corridor. These phenomena are in line with the test expectation of the guidelines.

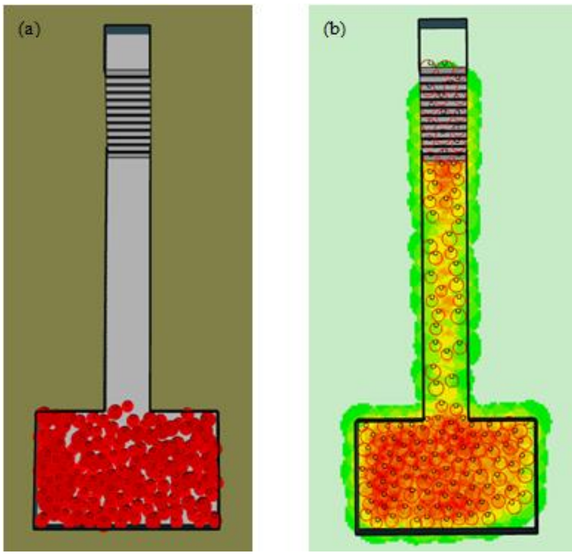

Figure C16: 150 persons walking from a room to a stair via a corridor and the heat map

TEST 12: Flow Density Relation

There is no standard scenario in detail for this test. The guidelines only specify that there is a corridor without any obstructions. The expected result is that the flow of persons in the corridor is generally smaller at very high population densities compared with that at moderate densities. As shown in Figure C17, we set the corridor's width to be 2 m. A certain number of persons are initially located at an area (25 m × 2 m, marked in yellow). A virtual line (in blue) is used to get the flow passing through it. There is an area (2 m × 2 m, in green) to get the density near the line. When the initial number was set to be 50, 100, 150, and 200, we ran the simulation and recorded the flow (p/m/s) and the density (p/m^2) when persons were passing through the line and the area, as shown in Figure C18. It could be seen that when the density is low (the case in (a)) or very high (the case in (d)), the flow is smaller than that at moderate densities (the cases in (b) and (c)). (Note that the density can be recorded in each time step (0.05 second) while the flow should be calculated in a period of duration. We set the period to be 5 seconds. So the value of flow at time, for example, at 10th second, the line counts the passengers passing from 5th second to 10th second.)

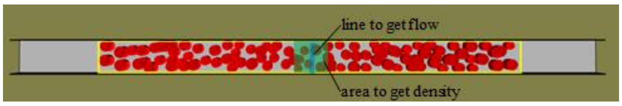

Figure C17: 100 persons walking in a corridor from left to right

C4 QUANTITATIVE VERIFICATION

It involves comparing model predictions with reliable data generated from evacuation demonstrations. At this stage of development there is insufficient reliable experimental data to allow a thorough quantitative verification of egress models. So the guidelines do not specify any test for this verification.

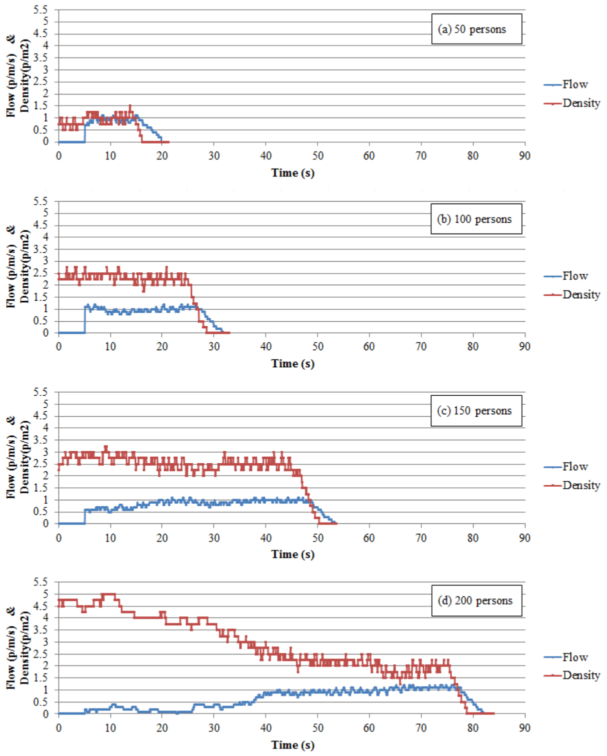

Figure C18: The recorded flow and density data at each time step

