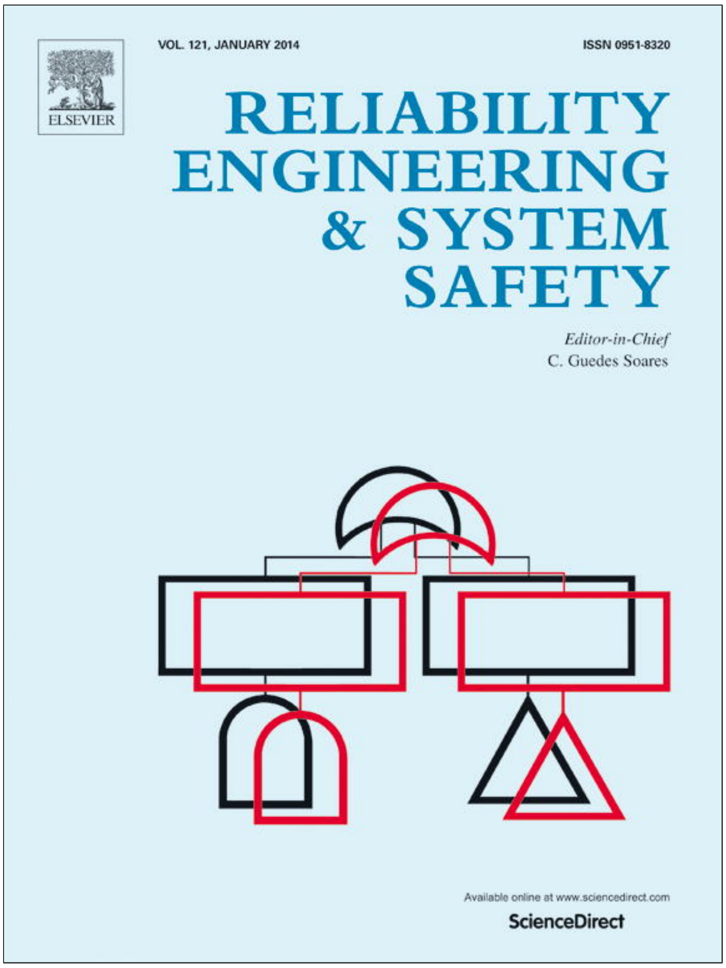
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A new simulation model for assessing aircraft emergency evacuation considering passenger physical characteristics

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ABSTRACT

Conducting a real aircraft evacuation trial is oftentimes unaffordable as it is extremely expensive and may cause severe injury to participants. Simulation models as an alternative have been used to overcome the aforementioned issues in recent years. This paper proposes a new simulation model for emergency evacuation of civil aircraft. Its unique features and advantages over the existing models are twofold: (1) passengers' critical physical characteristics, e.g. waist size, gender, age, and disabilities, which impact the movement and egress time of individual evacuee from a statistical viewpoint, are taken into account in the new model. (2) Improvements are made to enhance the accuracy of the simulation model from three aspects. First, the staggered mesh discretization method together with the agent-based approach is utilized to simulate movements of individual passengers in an emergency evacuation process. Second, each node discretized to represent cabin space in the new model can contain more than one passenger if they are moving in the same direction. Finally, each individual passenger is able to change his/her evacuation route in a real-time manner based upon the distance from the current position to the target exit and the queue length. The effectiveness of the proposed simulation model is demonstrated on Boeing 767-300 aircraft.

1. Introduction

As investigated by the National Transportation Safety Board (NTSB), 78% of all fatalities occurred post-impact, of 95.4% were resulted from smoke inhalation and burns due to slow and inefficient evacuations [1]. If post-impact crash survivors can be evacuated promptly, the survival rate would be increased by 98.3% as claimed by NTSB [1]. As reported by the NTSB, the inefficient evacuation in the Asiana Airlines Boeing 777 crash caused injuries on July 6, 2013. On the other hand, Boeing company forecasts that global airlines will require 33,500 new aircraft worth 4 trillion US dollars from 2011–2030, a 60% increase compared to the past decade. Along with bringing new technologies and concepts into aircraft design and manufacturing, the safety of newly designed aircraft also greatly concerns both manufacturers and passengers [2].

In the case of an emergency, to ensure the safe and rapid evacuation of passengers from aircraft is of paramount importance. In order to meet domestic and international regulations and obtain the service permission, a suite of tests must be conducted to ensure that emergency evacuation requirements are fully complied by any newly designed civil aircraft. The International Civil Aviation Organization (ICAO) requires that the aircraft shall be equipped with sufficient emergency exits to allow maximum opportunity for cabin evacuation within an appropriate time period [3]. More specifically, FAA certification criteria and test methods are integral to evaluating the evacuation capability of new aircraft, and it requires a full-scale evacuation demonstration that all passengers and crew must be evacuated from the cabin of an aircraft to the ground under simulated emergency conditions within 90 s, with only a half of emergency exits available [4]. The commonly accepted way of demonstrating this capability is to perform a series of full-scale trials using an appropriate mix of passengers [5]. However, in most cases, these results are kept confidential due to commercial reasons. On the other hand, the extremely expensive cost and the potential threat of injury to the participants forbid the use of the real evacuation trials. For instance, it costs around two million US dollars to conduct a single evacuation trial for a wide-body aircraft [6]. Additionally, during seven full-scale demonstrations conducted by aircraft manufacturers between 1972 and 1980, 166 of 2571 total participants (around 6.5%) got injuries, such as broken bones and paralysis [6]. As both Airbus and Boeing companies are planning to launch a new generation of aircraft, also called Very Large Transport Aircraft (VLTA), carrying up as many as 1000 passengers [7,8], emergency evacuation of VLTA in the event of survivable crash, therefore, poses a challenge for aircraft manufacturers and certification authorities [9,10].

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To overcome all of the aforementioned shortfalls in real evacuation trials, computer models have been developed recently to simulate the evacuation process instead of executing real evacuation trials. The simulation models can not only greatly reduce expenditure and void potential risks in real evacuation trials, but also provide insights on the evacuation performance of a new aircraft to manufacturers before the aircraft is physically built and/or put into service. In general, existing evacuation models can be categorized into network flow models and network node models. The former treats evacuees of a simulator as if they are fluid in a pipeline, but they cannot characterize movements of evacuees separately and differentiate behaviors of each individual passenger. This type of models is usually used to simulate building evacuation with a huge population. Exit 89 [11], GPSS [12], and EVACNET [13] are representative simulators using network flow models. The network node models, on the other hand, represent the entire simulation environment via a network of nodes. Evacuees pass from one node to another until they completely evacuate. Based upon the size of the nodes in the model, network node models can be further classified into the coarse network approach and the fine network approach, offering different extents of accuracy. As the network node models are capable of characterizing the respective behaviors of each individual evacuee, it can therefore provide details of an evacuation process and more accurate results. For example, EXODUS [14], ARCEVAC [15], and airEXODUS [16] are those which are capable of characterizing the behaviors of evacuees individually and tracking every evacuee throughout a simulation process. Each individual in the evacuee population could be assigned a set of properties that would determine evacuees' behaviors.

Most of the existing evacuation models were developed for building industry, and over 30 different evacuation models are used for building design and certification [17–19]. For aircraft evacuation, airEXODUS is one of the most extensively used aircraft evacuation software and still under development [16,20,21]. In recent years, several simulation models were developed for aircraft evacuation. For example, Galea et al. [22] considered the impact of aircraft post-crash fire in evacuation simulation. Kirchner et al. [23] took into account the competitive behaviors of individual evacuees in the aircraft emergency evacuation. Miyoshi and Nakayasu [24] developed an evacuation model considering the influence of passengers' emotion. Xue and Blocbaum [25] investigated the individual and interactive effects of cabin configuration (e.g. fuselage width, aisle width, exit aperture width, etc.) on aircraft evacuation efficiency. Most recently, with development of artificial intelligence techniques, artificial passengers in simulation models are designed to mimic human intelligence with respect to their surrounding environment to more accurately represent decision-making process of evacuees in aircraft evacuation [26–29], and it is called agent-based approach.

It is noteworthy that there is still a need for improving the accuracy and credibility of aircraft evacuation models to better reflect the real evacuation processes in emergency conditions. For example, as observed in real evacuation trials [30], the physical characteristics of evacuees, like waist size, gender, age, and disability, have critical impact on the egress time in aircraft emergency evacuation. Koo and Kim [31] assessed the impact of disabled residents on the evacuation in high-rise building. Their work indicated that the disabled population could lead to a significant increase of the egress time in emergency evacuation. These physical characteristics of passengers, however, have been rarely taken into account in existing aircraft evacuation simulation models. Moreover, in the most reported works, the cabin space are divided into a set of equal-size nodes [23,24,26], e.g. 0.5 m × 0.5 m square nodes are used by EXODUS and 0.2 m × 0.2 m square are adopted by SIMULEX. Also, the limitation that each node can be occupied by only one passenger in these models would result inaccurate representation of evacuation processes as in emergency conditions evacuees stay next to each other very closely. Last but not least, artificial passengers models in exiting models will choose the nearest available exit as the target exit and never change their target exit throughout the entire evacuation process (as seen in Refs. [23,24,26,32]). However, in reality, the flow rate of exits varies from one type of exits to another. The exit with a higher flow rate will be less crowded and has a shorter queue length. This may affect the passengers' choice of the target exit and evacuation route.

With the aim of addressing the aforementioned issues, an agent-based approach in conjunction with a multi-level fine network representation is proposed in this work to emulate the aircraft evacuation process. The contribution of this work lies in taking account of the influences of passengers' physical characteristics on the evacuation time, and introduction of several improvements to make simulation closer to reality.

The rest of this paper is organized as follows: Section 2 describes the proposed model for simulator. Section 3 introduces a new model for characterizing passengers' evacuation behavior with respect to their physical characteristics, along with the proposed evacuation route selection strategy. A case study together with the comparative and sensitivity analysis is detailed in Section 4, and it is followed by a brief closure in Section 5.

2. The proposed model for simulator

2.1. Discretization of cabin space

Compared to other simulation environments, like buildings, parks, and public squares etc., the aircraft has several unique features, such as complex structure, numerous obstructions on evacuation paths, and narrow legroom, etc. In most reported aircraft evacuation simulation models, the internal structure of an aircraft can be represented by a set of interconnected two-dimensional “nodes”, each of which can be either empty or occupied by a passenger.

To facilitate and simplify simulation program, traditional network node models discretize cabin space of an aircraft into small equal-size square nodes, say 0.4 m × 0.4 m, in most studies [23,24,26]. However, it appears that the width of legroom is much smaller than the seat size as observed from the cabin layout of Airbus A320 as shown in Fig. 1. Actually, in the economy class of a commercial civil aircraft, the width of legroom is around 0.3 m, whereas the seat is around 0.5 m.

Even though extreme fine network nodes can be used to improve the accuracy of representing cabin space in a simulation model, it requires that the sizes of legroom, seat, and toilets must be integral multiples of the finer nodes. The number of nodes will be increased exponentially and consequently lead to a tremendous computational burden and time. To achieve a good trade-off between the accuracy of layout representation and computational burden, instead of using equal-size nodes as many reported works [23,24,26], a cabin space in our work is subdivided into multiple levels of fine nodes with different sizes. The seat pitch (the space between each seat anchor) of economy class of both Boeing and Airbus aircraft fall in the range of [0.787 m, 0.863 m] whereas the width of seat in the range of [0.45 m, 0.53 m]. In addition, referring to the latest report of human physical dimensions [33], the width between elbows of the 95th percentile of males is less than 0.5 m; whereas the depth of chest is less than 0.28 m. The seat pitch (0.8 m × 0.5 m) of our simulation model of a Boeing 767-300 is thereby divided into seat nodes and legroom nodes with different sizes, say 0.5 m × 0.5 m and 0.3 m × 0.5 m for the seat node and

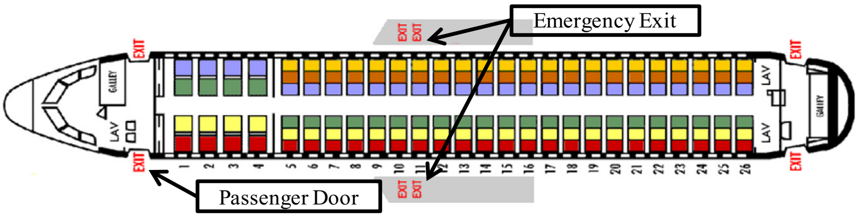

Fig. 1. The cabin layout of Airbus A320.

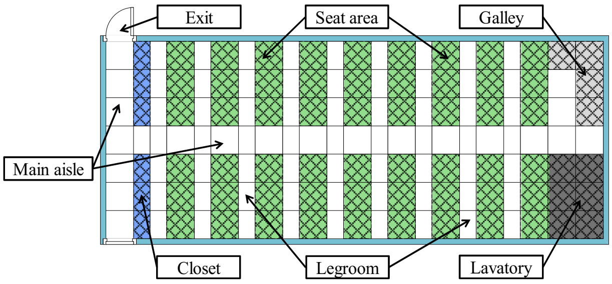

Fig. 2. The proposed discretization of a cabin space.

the legroom node respectively. An illustration of such a discretization strategy is shown in Fig. 2.

A passenger staying in the node of the aisle can move, at most, in the four directions as shown in Fig. 3. It should be noted here that in our simulation model, it is not necessary that any node must be occupied by only one passenger as many reported works [23,26,32]. In our model, artificial passengers may occupy a part of neighboring nodes simultaneously. Any node, on the other hand, may contain more than one passenger. This strategy is able to reflect the real situation that passengers can stay next to each other very closely when they evacuate in an emergency scenario. In addition, each node contains three properties, namely type, value, and position. Any node belongs to one of two types, either obstacle (such as seats, toilets, etc.) or unconstrained one (legroom, aisle, and exit). The value of a node indicates the distance from the current position to one of the available exits. The positions of the borders and center of a node in the coordinate system of cabin space are recorded by the position property.

2.2. Evacuation map

The evacuation map shows the information about simulation environment, such as locations of obstacles and the distance from a seat to an exit. It is assumed to be known in advance by all passengers and will be used as the basis in simulation. In our study, an evacuation map is generated for each available exit. An example of the evacuation map for the front right exit is illustrated in Fig. 4. In the proposed simulation model, passengers are able to identify and choose the least crowded escape route to evacuate. If more than one route has identical queue length, the shortest route will be chosen by passengers. The details of route planning will be elaborated in Section 3.

2.3. Types of exits

FAA defined seven types of exits for a passenger aircraft (see 25.807 (a) of the FAR [4]) with heights in a range of 0.48 m and 1.83 m. The physical dimensions of exits have considerable impacts on the evacuation efficiency, i.e. the time spent by passengers to pass through an exit. A smaller exit has a less evacuation efficiency as it requires more time to pass through. In our study, four types of commonly used exits are considered,

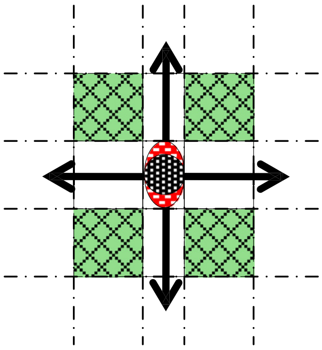

Fig. 3. Directions of movement for a passenger staying at the aisle.

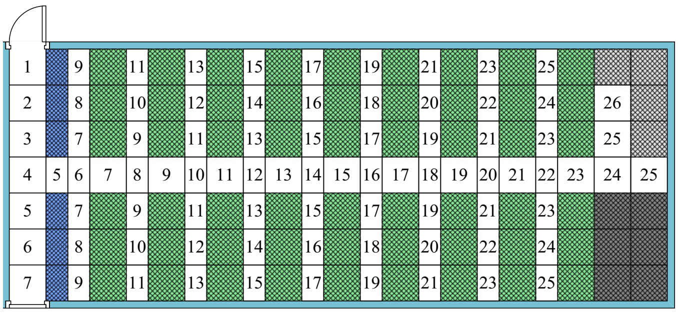

Fig. 4. An evacuation map generated for the front right exit.

Table 1
The average flow rate of each type of exits in our study [30,48,49].

Types of exits	Type-A	Type-C	Type-I	Type-III
Average flow rate (s/person)	0.475 s	0.937 s	1.282 s	1.565 s
Exit opening time (s)	2.250 s	2.250 s	4.610 s	5.295 s

which are Type-A, Type-C, Type-I, and Type-III. In real emergency evacuation, the floor level exits (known as Type-A, Type-B, and Type-C) are most likely operated by the crew [20], but the emergency exits (such as Type-III) are oftentimes opened by passengers. The average flow rate and the time of opening exits are tabulated in Table 1.

3. The proposed model for passengers' evacuation

By looking into the data reported in actual evacuation trials [30], it is found that in an emergency scenario, the physical characteristics of a passenger, like waist size, gender, age, and disability etc., yield significant impact on evacuation behavior and performance (egress time) of the passenger; whereas the impact of group density, hatch disposal location, and passenger's height are trivial. In our work, the relationship between the passengers' characteristics and their evacuation time is established based on the real experimental data reported in literature. In addition, artificial passengers generated in our simulation model must possess intelligence that they can perceive the external environments and plan their evacuation routes, especially promptly change their routes in a reasonable way.

3.1. *Influencing factors in aircraft evacuation*

Similar to the observations in real evacuation trials [30,34], in our evacuation model, movements of passengers are influenced by both design factors (e.g. the location of exits, the width of legroom [30,34]) and physical characteristics of passengers [30]. As observed in real trials, the extent of impact of each influencing factor is extremely different. The significant ones among many physical characteristics of evacuees include waist size, gender, and age as shown in Fig. 5. The influencing factor with a greater percentage over the total effect (see the numbers in Fig. 5) has more important contribution to egress time. The impact of each physical characteristic on egress time is elaborated as follows:

3.1.1. *Gender*

Based on the reported works [35], the percentage of male passengers is slightly higher than females. The reaction time of evacuation varies with gender. Figs. 6 and 7 respectively show the percentages of male and female in the real population of airline passengers and the reaction time with respect to different genders.

3.1.2. *Age*

Among 1859 records of airline passengers in AASK V4.0, the average age of female passengers is 39.9 years slightly younger than male passengers with 40.8 years of average age. However, as the minor and senior with age younger than 18 years or older than 65 years are not allowed to participate in evacuation demonstration due to the child labor laws and safety consideration, no experimental data associated with actual egress tests of this age group of the population can be found. The passengers with age younger than 18 years or older than 65 years are, therefore, eliminated from passenger samples generated in our simulation model. Figs. 8 and 9 plot the age distribution of actual air travelers and the influence of age on the egress time respectively.

3.1.3. *Waist size*

It may cause difficulty for passengers to move in an aircraft if their waist circumference is extremely large. As shown in Fig. 5, the waist size is a major influencing factor in the evacuation process. The waist size has a strong statistical correlation with age, gender, and race, and in most cases, an elder passenger may have a

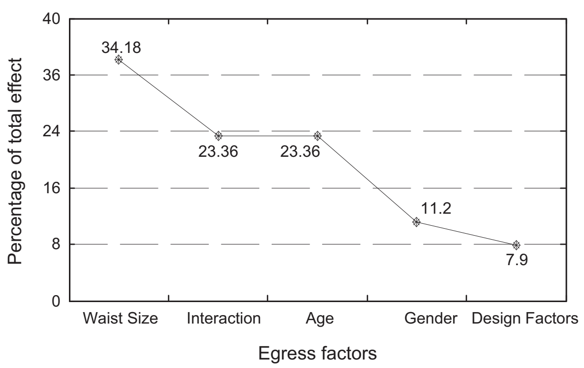

Fig. 5. The importance of influencing factors in an aircraft evacuation [30].

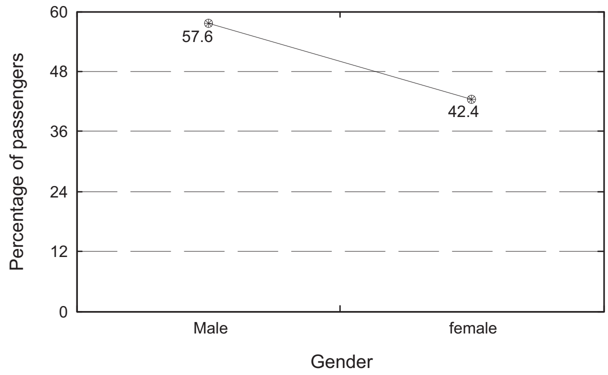

Fig. 6. The percentages of the male and female passengers [35].

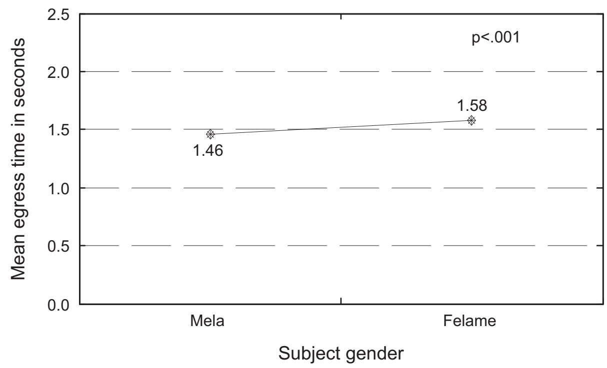

Fig. 7. The influence of gender on the egress time [30].

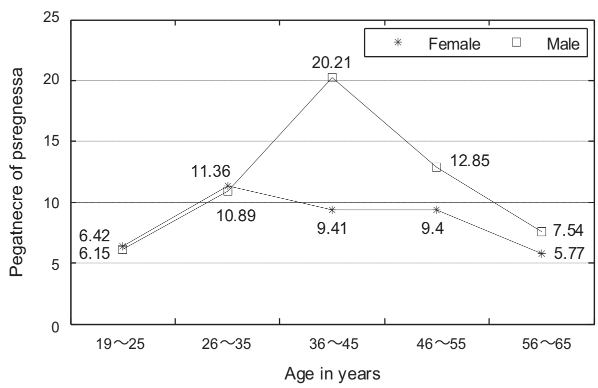

Fig. 8. The age distribution of the passengers [30].

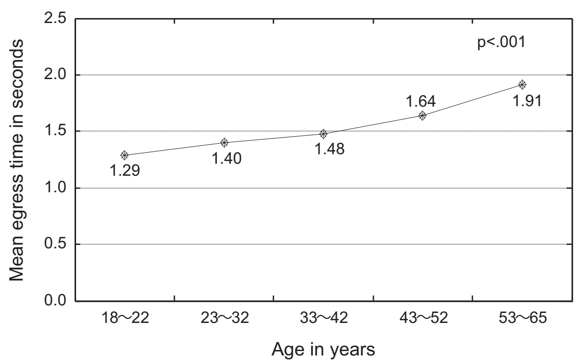

Fig. 9. The influence of age on the egress time [30].

Table 2
The distributions of waist size with respect to gender and age [50].

Waist circumference in centimeters for adults aged 19–69 years by gender and age											
Gender	Age (yr)	Mean (cm)	Percentile								
			5th	10th	15th	25th	50th	75th	85th	90th	95th
Male	19	88.1	70.0	72.2	74.0	76.5	83.5	96.8	106	110.9	118.6
	20–29	93.8	73.5	76.8	78.8	82.8	90.9	101.3	108.4	113.3	123.9
	30–39	98.2	78.9	81.9	85.1	88.9	96.8	105.7	111.4	115.0	120.7
	40–49	102.9	82.4	86.6	89.3	93.4	101.8	111.4	115.3	119.6	128.6
	50–59	103.9	83.6	87.1	90.2	94.0	102.9	111.1	117.3	122.3	129.7
	60–69	106.7	84.6	90.2	93.0	97.5	105.5	115.6	120.8	124.6	129.9
Female	19	85.8	–	69.5	71.5	73.6	81.3	92.7	102.9	107.8	–
	20–29	88.2	68.6	71.7	73.1	75.8	84.3	96.7	106.1	113.5	119.5
	30–39	91.6	71.6	74.1	76.2	79.6	89.3	100.2	106.9	111.8	121.1
	40–49	95.2	72.9	76.2	79.3	83.7	92.6	105.4	111.4	116.8	125.5
	50–59	96.9	72.3	76.3	78.8	84.8	95.4	108.1	113.8	117.7	127.7
	60–69	98.6	75.7	79.8	82.8	88.1	97.1	108.8	114.8	118.9	123.8

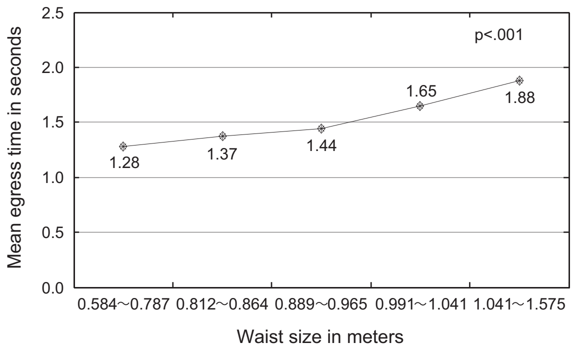

Fig. 10. The influence of waist size on the evacuation time [30].

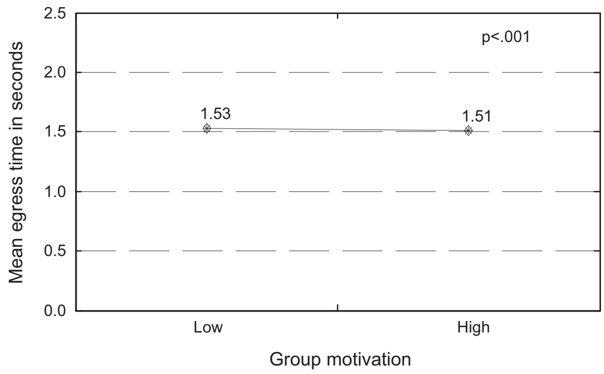

Fig. 11. The influence of group motivation on the evacuation time [30].

larger waist size. Also, males usually have a greater waist size than females. The distribution of waist size and its influence on the egress time is shown in Table 2 and Fig. 10 respectively.

3.1.4. Group motivation

In a real emergency situation, passengers may scramble to reach egress exits as soon as possible. This may become more serious when the accident situation is more grievous. As shown in Fig. 5, interaction between individual evacuees has an impact on the evacuation performance of individual passenger. The influence of group motivation is therefore taken into consideration in our work. The egress time with respect to the extent of group motivation is shown in Fig. 11.

3.1.5. Legroom configuration

In the actual layout of civil aircraft, the narrow legroom leading to the main aisle may bring difficulties to the passengers to pass through. The influence of the legroom configuration on the evacuation time must be thereby taken into account. Fig. 12 illustrates the relationship between the legroom width and evacuation time, a larger legroom leads to a shorter egress time.

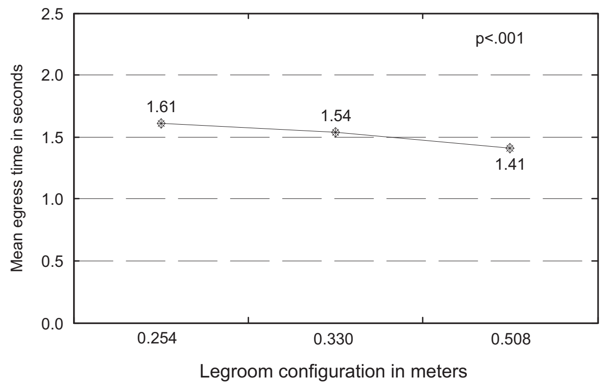

Fig. 12. The influence of legroom configuration on the egress time [30].

3.2. Locomotion of passengers

An important characteristic of evacuees identified in *Life Safety Code*® for fire evacuation is the speed which is an essential property in the representation of human physical ability in evacuation models [36]. The speed of any passenger consists of three components in our work, i.e. main aisle speed (V^l_{aisle}), legroom speed ($V^l_{legroom}$), and exit speed (V^l_{exit}). If nobody is staying ahead, the speed of an evacuee completely depends on the location of the evacuee, say aisle, legroom, or exit; otherwise the evacuee moves with the same speed as the front passenger.

The speed of movement in aisle region is related to the physical characteristics of each passenger. As reported in Ref. [37], the average rate of movement through aisle for unimpaired passengers at horizontal floor is 2.44 m/s, whereas the mean time of passing through exit (Type-III) for individual passenger is 1.565 s [30]. If the thickness of cabin wall is 0.18 m (the thickness of the cabin wall of Airbus is 0.112–0.189 m [38]), the average speed of passing through Type-III exit equals to 0.115 m/s, that is to say, the average speed of movement in aisle region is 21.22 times larger than that of the Type-III exit. It is reasonable to assume that such a relationship between the speed in aisle region and exit holds for all passengers, thus the speed of each passenger in aisle region can be approximately computed based on their speed at the time of passing through the Type-III exit. It reads

$$V^l_{aisle} = 21.22 \times V^l_{exit(Type-III)}, \tag{1}$$

where $V^l_{exit(Type-III)}$ denotes the speed of evacuee l passing through the Type-III exit; V^l_{aisle} is the speed of evacuee l in the aisle region.

In the real egress trials reported in the literature [30], the egress time of an individual passenger is defined as the duration from the moment when evacuee passenger completely passes through the exit opening to the moment when the next passenger completely passes through the exit opening. Due to the impact from physical characteristics, egress time at exit may vary from person to person. The velocity of each individual passenger at exit can be expressed as

$$V^l_{exit(Type-III)} = \frac{L_{exit}}{T^l_{total}} = \frac{L_{exit}}{\alpha T^l_g + \beta T^l_a + \gamma T^l_{wc} + \delta T_{gm} + \varepsilon T_{df}}, \tag{2}$$

where L_{exit} is the thickness of cabin wall; T^l_{total} denotes the total time of passenger l passing through the Type-III exit; T^l_g, T^l_a, T^l_{wc}, T_{gm}, and T_{df} indicate the egress time in real evacuation trials with respect to each influencing factor, i.e. gender, age, waist size, group motivation, and design factors (the width of legroom in our work), respectively. It is noted here that T_{gm} and T_{df} are treated as fixed values for all passengers. For each passenger sample in our model, depending on its physical characteristics, T^l_g, T^l_a, and T^l_{wc} take values from Figs. 7, 9 and 10 respectively. Here, T_{gm} is related to the severity of an accident, and it takes value from Fig. 11, T_{df} is associated with the space of legroom of the simulated aircraft as shown in Fig. 12, and α, β, γ, δ, and ε are the weights (or importance) of each influencing factor with respect to the egress time, and their values are taken from Fig. 5.

The moving speed of an individual passenger l in legroom can be calculated by

$$V^l_{legroom} = \frac{1.41}{1.54} \times V^l_{aisle}, \tag{3}$$

where 1.54 and 1.41 correspond to the average egress time when the width of the legroom is 0.330 m and 0.508 m respectively as shown in Fig. 12. Suppose the velocity of passenger l moving along legroom is proportional to the velocity of moving along the aisle, we can therefore use Eq. (3) to compute the moving speed of passengers in legroom as it can be assumed that the moving speed along aisle with the width of 0.5 m is nearly same as in the legroom with the width of 0.508 m. Additionally, in our model, it assumes that the speed of passenger l passing through other types of exits is proportional to the speed of passing through Type-III exit, and such ratio equals to the average flow rate of Type-III exit (as listed in Table 1) over that of one type of exit. Thus, one has

$$\begin{cases} V^l_{exit(Type-A)} = \frac{1.565}{0.475} \times V^l_{exit(Type-III)} \\ V^l_{exit(Type-C)} = \frac{1.565}{0.937} \times V^l_{exit(Type-III)} . \\ V^l_{exit(Type-I)} = \frac{1.565}{1.282} \times V^l_{exit(Type-III)} \end{cases} \tag{4}$$

3.3. Passengers' behavior

In actual aviation accidents, due to panic, some passengers may behave extraordinarily, such as seat climbing and conflicts [35]. These abnormal behaviors are not considered in this simulation, and it is assumed that all passengers try to escape cabin as quickly as possible in a systematic order.

3.3.1. Route selection

Once start evacuating, every passenger in an aircraft has to choose an available exit to evacuate from the cabin. It has been observed in actual accident records that more than 70% of passengers tend to use the nearest exit [39]. Therefore, in most conventional aircraft simulation models, artificial passengers intend to choose the nearest available exit as target exit and generate the corresponding evacuation route, that is, the distance is the only criteria for choosing the evacuation route for each individual passenger. As the flow rate of each type of exits is much more distinct (see Table 1), it usually results in a poor distribution of evacuating passengers among available exits during the simulation process (as seen in Refs. [23,24,26,32]). From the simulation point of view, the distance from one passenger to any available exit can be computed accurately and readily, but it is not an easy task to visually measure and compare lengths of two routes in actual evacuation trials or real emergency evacuations especially the difference of the distances of two routes are not quite obvious. On the other hand, passengers are more likely to choose the route based on not only the shortest distance, but also the amount of evacuees in a queue which can be easily seen. Taking this point into consideration, a new route selection rule which uses both the distance to an exit and the queue length to determine the evacuation route of an individual passenger is proposed in this work. With this rule, any passenger can change his/her choice in a real-time manner if he/she realizes one of other exits can make him/her escape from the cabin more quickly. To achieve this purpose, a threshold N_{RC} is preset in our simulation model. If the number of evacuees queuing in a new route minus that of the old route is equal or greater than N_{RC}, an evacuee is prone to switch to the new route with fewer passengers in the queue.

During the evacuation of wide-body civil aircraft, if a passenger selects an exit (e.g. Exit A or Exit B in Fig. 13) as the target exit to evacuate, he/she may oftentimes have two paths (Path 1 and Path 2 as shown in Fig. 13) to move along if these two paths have the same queue length. Passengers' choice of these two paths oftentimes exhibits randomness specifically in emergency situations. The randomness (or uncertainty) of evacuees' choice of evacuation routes in an emergency situation has been also observed in pedestrian evacuation [40]. In our model, we assume that a passenger in such situation will have a probability of P_{path} $(0 < P_{path} < 1)$ to move along path 1 (pass through the main aisle first rather than legroom) and $1-P_{path}$ for path 2 (pass through legroom first rather than main aisle).

3.3.2. Time of releasing seat belt, egressing from seat, and opening emergency exit door

At the beginning of an evacuation, passengers must first release the fastened seat belt, and then egress from their seats. The average time required to release a seat belt and egress from the seat is tabulated in Tables 3 and 4, respectively. By referring to the data in Tables 3 and 4, it is found that the average seat belt releasing time and the average egress time from a seat is not significantly different for three belt configurations. In the real evacuation drills, the

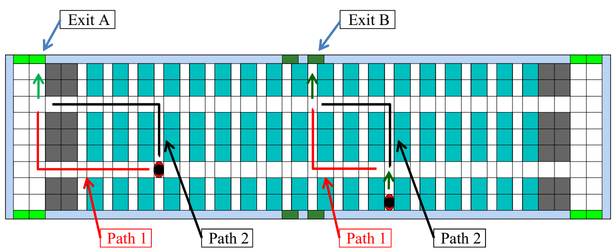

Fig. 13. Two possible paths to an exit.

Table 3
Average time to release belt [47].

Latch release angle (deg)	Sequence of trial (s)			
	1	2	3	Average
30	0.968	0.883	0.957	0.9360
60	0.809	1.000	1.000	0.9363
90	1.032	0.926	0.851	0.9363

Table 4
Average egress time from seat [47].

Latch release angle (deg)	Sequence of trial (s)			
	1	2	3	Average
30	2.460	2.160	2.210	2.2770
60	2.090	2.360	2.200	2.2170
90	2.290	2.110	2.230	2.2100

passenger who first reaches an emergency exit (refer to the overwing exits) will open the emergency door immediately. To take these amounts of time into consideration, in our model, we assume that the seat belt releasing time, the time of egressing from a seat, and the time of opening emergency exit door are related to the exit egress time of passengers. Put another way, the passenger who has a faster speed of movement can prepare for evacuation and open the emergency door in a shorter time. Based on the relationship between the average speed of passenger moving along the aisle and the average belt releasing time, the time of egressing from the seat, and the time of opening an emergency door, one has

$$\begin{cases} T^l_{br} = \frac{0.936\ s}{2.44\ m/s} \times V^l_{aisle} \\ T^l_{es} = \frac{2.235\ s}{2.44\ m/s} \times V^l_{aisle}\ , \\ T^l_{ed} = \frac{5.295\ s}{2.44\ m/s} \times V^l_{aisle} \end{cases} \tag{5}$$

where 2.44 m/s is the average speed of all passengers moving along the aisle (the width is 0.5 m), values of the average time of releasing the seat belt (0.936 s), egressing from seat (2.235 s), and opening emergency door (5.295 s) are taken values from Tables 1, 3 and 4, respectively. Here, T^l_{br}, T^l_{es}, T^l_{ed} are the time for releasing a seat belt, egressing from the seat, and opening an emergency door exit (Type-III) for passenger l, respectively.

3.3.3. *Moving rules*

In most reported fine network node models, the cabin of an aircraft is divided into a set of square nodes with an identical size equal to the space occupied by a passenger in a dense crowd. Thereby, all movements of passengers are subjected to the restriction that a node can only be occupied by, at most, one passenger at any time unit. If the target node is occupied by another passenger at this moment, a passenger has to wait for moving into the target node until the node is unoccupied (such as Refs. [23,26,32]). By this way, passengers' movement can be dramatically simplified and coded readily. However, this simplified treatment will cause a "gap" (see Fig. 14) between passengers in the process of moving, because a node will be in an occupied status until the occupant is completely moved out. It lacks reality in nature since the passengers will stay closely next to each other and there is no "gap" between passengers in real emergency evacuation.

To overcome the aforementioned issue, artificial passengers in our proposed model are permitted to move towards their target node with small steps according to their speed of movement. Any

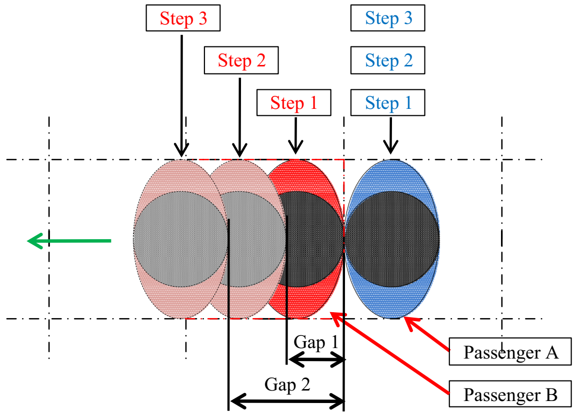

Fig. 14. The "gap" between passengers in the moving process.

node may contain simultaneously more than one passenger at a time, but passengers are not allowed to overlap with each other. The rules of movement of each passenger are as follows:

(1) Passengers moving along the same direction can enter the same node with no "gap" between two passengers.
(2) Conflicts may arise when more than one passenger with different moving directions intends to move into the same node. In our model, passengers with a higher moving speed have a greater chance (i.e. probability) to move into their target node.
(3) In any time unit (i.e. the minimum simulation step), all passengers have opportunities to move. All passengers are sorted by the distance from their current positions to their target exit. Those who have a smaller distance to exit will move first within the same time unit.

Fig. 15 is the flowchart of a single passenger l evacuating from a cabin in our proposed simulation model. *DF* denotes the distance from passenger l to his/her front passenger; *SL* is the step length of the passenger l can move within a time unit Δ_t according to his speed at the current location.

As shown in Fig. 15, in the simulation process, if the next node is empty, a passenger can move into the node with his/her maximum speed; otherwise, he/she can only move into the next node with the same speed as the front passenger.

3.3.4. *Simulation steps and timing*

In practice, all passengers move simultaneously within a time unit of the actual evacuation process. Nevertheless, it is very difficult to realize this simultaneity precisely. An approximation is used in this work to overcome this issue: every passenger takes a time unit Δ_t (i.e. the minimum simulation step) to complete his/her movement. After all passengers move a single step in a cycle, the simulation time for this cycle only increases Δ_t, supposing the actions of all passengers complete simultaneously within the time unit Δ_t. Thereby, the overall evacuation time for the simulation is

$$T_{total} = N \times \Delta_t, \tag{6}$$

where N is the total number of cycles of the entire simulation process.

3.4. *Passenger samples*

All artificially generated passengers in an evacuation simulation must possess the same distributions of gender, age, waist circumference, and many other physical characteristics with actual

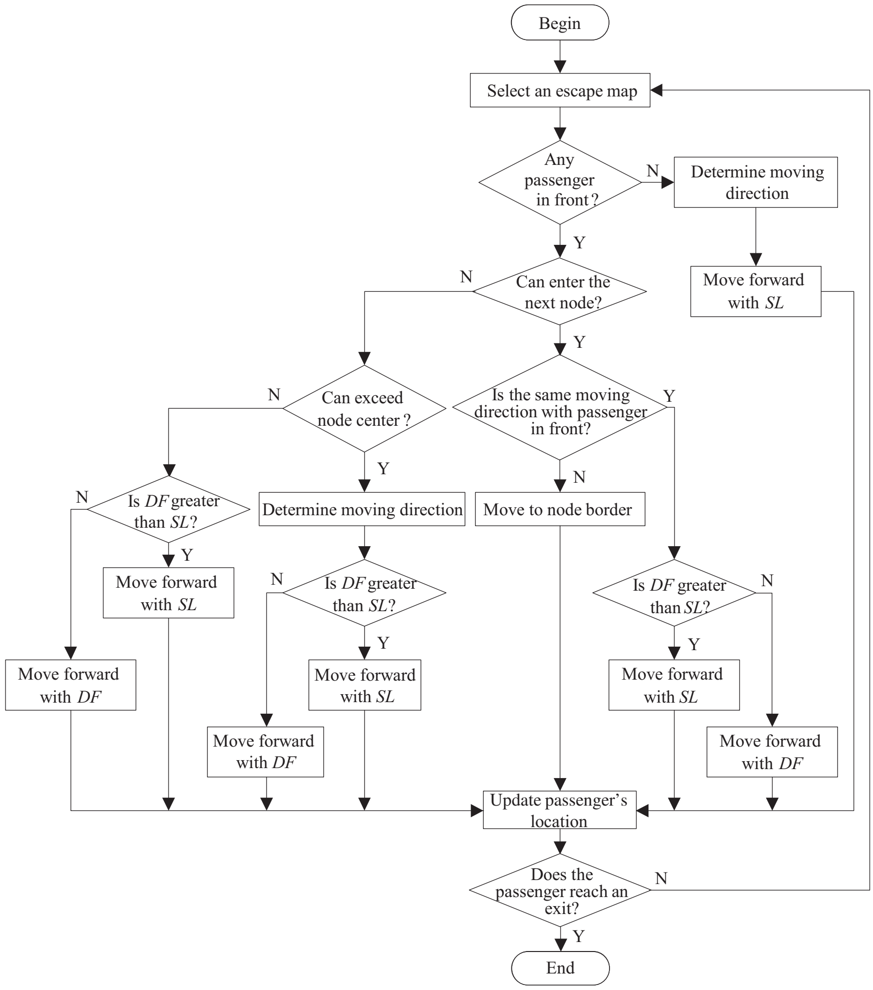

Fig. 15. The flowchart of the evacuation process for a passenger.

airline passengers. Each passenger has his/her own physical characteristics generated from statistical distributions, and these characteristics, in turn, determine his/her evacuation speed in simulation. The physical characteristics of artificial passengers are generated in accordance with AASK V4.0 and many other experimental results from literature [35].

In recent years, as the legislation begins protecting rights of people with disability and facilities for assisting disabled airline passengers have been built, a significant and increasing number of disabled people start to travel by air [41]. From 2002 to 2005, the percentage of disabled adults traveling by airplane stays around 31% (or 9.6 million) every year [42]. Most likely, passengers with disabilities will slow down the evacuation process of other passengers due to their slower moving speed. Therefore, in our simulation, the disability as one of the physical characteristics of passengers is also considered. Based on Refs. [37,43], the percentage of each category of disabled passengers and their evacuation speed along the main aisle of an aircraft are shown in Table 5. These data are also incorporated in our simulation model.

Table 5
Percentage of disabled passenger with age from 18 to 64 [37,43].

Category of disability	Percentage (%)	Average rate of moving through the aisle (m/s)
Hearing difficulty	0.250	1.42
Vision difficulty	0.200	1.00
Cognitive difficulty	0.487	1.12
Ambulatory difficulty	0.618	0.81
Self-care and independent living difficulty	0.618	0.48
Non-disabled	97.827	2.44

4. Case study

4.1. Evacuation simulation for Boeing 767-300

Based on the proposed models, a simulation program has been developed in our study. The graphical user interface (GUI) of the program is shown in Fig. 16. The number of seats per row, the number of rows of seats, the number, type, and location of exits, are input variables of the simulator, offering a flexibility to conduct simulation for most types of aircraft. The total evacuation time is the output. As shown in Fig. 16, the blue nodes represent seats; the white nodes denote the legroom and aisle; the light blue frame is the cabin wall, and the green rectangles indicate exits. The parameter settings for Boeing 767-300 in our simulation program are presented in Table 6. The parameter settings of the simulation are tabulated in Table 7.

Some of parameter settings, such as the N_{RC} and P_{path}, may have impacts on the total evacuation performance. A sensitivity analysis will be conducted in the ensuing section to examine how sensitive the evacuation time is with respect to these parameters.

Fig. 17 shows an intermediate step of a simulation process. All passengers (denoted by red ellipses with black dots in the center, the disabled passengers are denoted by yellow ellipses) follow the moving rules proposed in our work.

The evacuation simulation is first conducted for full non-disabled passengers under two conditions: (1) all exits are available; (2) only one side of exits is operable. As a comparative study, simulations for the aforementioned two conditions are also conducted in the case where disabled airline passengers exist. For each condition, simulations are performed 100 times with artificial passengers randomly generated based on the distributions of physical characteristics to yield the evacuation time in statistical sense. The means and the standard deviation (Std.) of evacuation time for all scenarios are tabulated in Table 8.

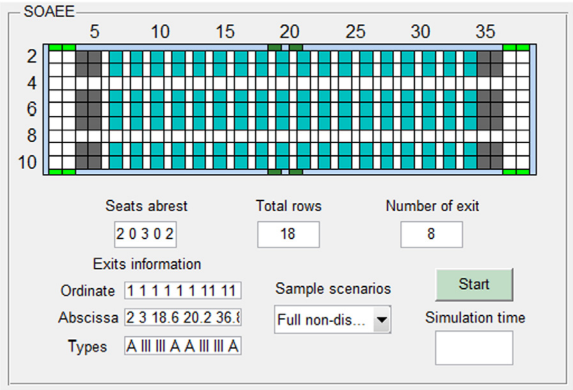

Fig. 16. The GUI of the developed simulation program. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 6
The basic configuration of Boeing 767-300 in simulation program [38].

Parameters	Value
Number of seats	294
Layout of seats abreast	2-3-2
Number of aisles	2
Seat pitch	0.80 m
Seat width	0.50 m
Aisle width	0.50 m
Legroom width	0.30 m
Sidewall thickness	0.18 m
Overwing exits	Two pairs of Type-III exits
Passenger doors	Two pairs of Type-A exits

Table 7
The parameter settings of the simulation model.

Parameters	Value
Threshold for changing route (N_{RC})	3
Probability of choosing aisle route (P_{path})	0.9
Probability of choosing legroom route ($1-P_{path}$)	0.1
Time unit (Δ_t)	0.05 s
Group motivation	High level

For the purpose of evacuating passengers quickly and safely in case of an emergency, escape slides can assist passengers in descending from aircraft exits to the ground. The additional delay time (around 8–10 s) for inflating escape slides after exit doors are completely open, passengers sliding along the escape slide and evacuating to a specified safe area on the ground is also included in our results. The mean of evacuation time of our simulation in the case where only one side of exits is available and no disabled passengers exist (the same as the certification trial case), is very close to the reported evacuation time which is 72.6 s for a full-scale certification performance of Boeing 767-300 [44].

As observed from Table 8, passengers with disabilities have a significant impact on the evacuation process in both conditions, i.e. all exits are available and only one side of exits can be opened. This indicates that special measures should be adopted to facilitate the evacuation of disabled passengers so as to ensure a fast evacuation process in emergency situations; otherwise, it may result in more serious injury and fatality due to tardiness of evacuations.

To illustrate the effect of considering the physical characteristics of every individual passenger, simulations are conducted for the case where all passengers have the same physical characteristics (the mean values of physical characteristics are assigned to all passengers). As one can see from Table 8, not only the mean of evacuation time exhibits a difference, but also the standard deviation and the range of simulation results with considering the diversity of physical characteristics of passengers are larger than that of the case where all passengers are exactly same. This information can provide a very useful insight for decision makers to take account of the potential perturbation of evacuation time due to variations of passengers' physical characteristics. In addition to this observation, it is also observed in our evacuation processes that passengers' behaviors and queues appear significant difference if the diversity of passengers' physical characteristics is considered.

4.2. Sensitivity analysis for parameter settings

The parameters in the simulation model, e.g. N_{RC} and P_{path}, may have impacts on simulation performance. In this section, sensitivity analysis is conducted to reveal how sensitive the evacuation performance is with respect to the values of these parameters.

4.2.1. Sensitivity of N_{RC}

We performed simulation 10 times by using the same passenger samples and fixed P_{path} at 0.9. The evacuation time versus N_{RC} is shown in Fig. 18 including the minimal, maximum, and mean of evacuation time from 10 simulation runs.

As observed from Fig. 18, when N_{RC} is set to zero, artificial passengers will choose the nearest exit as the target exit to escape. Passengers sticking to their target exit will lead to a serious deceasing of evacuation efficiency since different types of exits at different locations of an aircraft have distinct evacuation capacity. In contrast, if N_{RC} is a non-zero value, passengers will switch their target exit to a new one when the old route has N_{RC} or more passengers in the queue than that of a new route. As one can

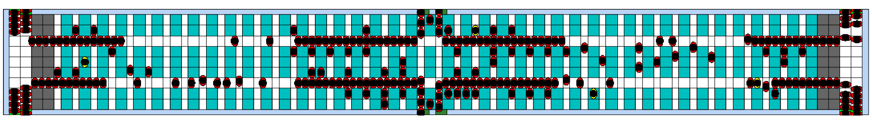

Fig. 17. An intermediate step of a simulation process. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 8
Simulation results of Boeing 767-300.

Full-scale evacuation simulation results of Boeing 767-300							
All exits are available				Only one side of exits is operable			
Passengers' type	Mean (s)	Std. (s)	Range (s)	Passengers' type	Mean (s)	Std. (s)	Range (s)
Full non-disabled passengers	47.12	1.78	44.55–52.70	Full non-disabled passengers	71.06	1.71	68.25–75.45
With disabled passengers	67.81	8.49	54.55–87.15	With disabled passengers	93.60	11.45	77.35–120.50
Passengers no physical differences	48.23	0.49	47.75–49.05	Passengers with no physical differences	69.53	0.53	68.95–70.60

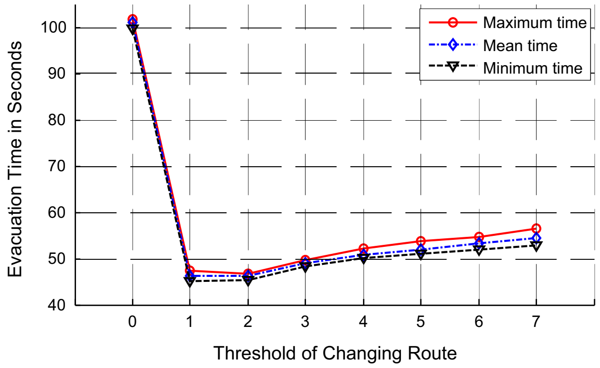

Fig. 18. The evacuation time versus the setting of N_{RC} (excluding time of sliding on escape slide and evacuating to the ground).

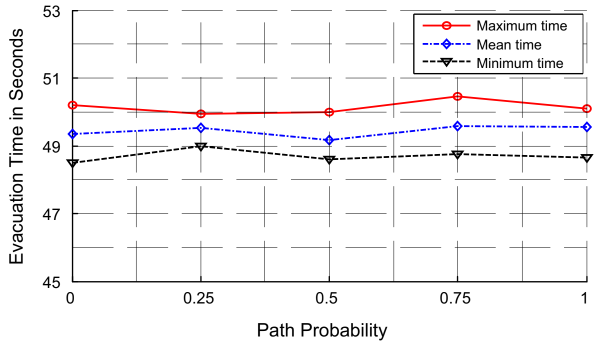

Fig. 19. The evacuation time versus the setting of P_{path} (excluding time of sliding on escape slide and evacuating to the ground).

see from Fig. 18, the evacuation time will be significantly reduced if N_{RC} is greater than zero. However, a larger value of N_{RC} leads to a longer evacuation time as observed in Fig. 18. An appropriate value should be set for N_{RC} in the simulation model.

4.2.2. Sensitivity of P_{path}

To examine the sensitivity of P_{path}, we performed evacuation simulation 10 times for each setting of P_{path}. The passenger samples are the same and N_{RC} is set to 3. Simulation results are delineated in Fig. 19. As observed from Fig. 19, the difference of mean evacuation time for different settings of P_{path} is less than 0.5 s. We therefore can conclude that P_{path} is a trivial factor in determining the evacuation performance.

5. Closure

In this paper, a new model is proposed to simulate the evacuation process of aircraft to verify the certification criteria without conducting real evacuation trials. To make the simulation closer to the reality, several critical physical characteristics of passengers which have significant impacts on the evacuation time as documented in real evacuation exercise are taken into consideration. In addition, a multi-level fine network model which allows subdividing the aircraft cabin into fine nodes with different sizes is developed in order to get a trade-off between the accuracy of simulation and computational burden. Moreover, the limitation that each node could be only occupied by one passenger has been overcome in the new model, and a set of route selection rules considering both the queue length and distance to exits are also proposed to reflect the decision and behavior of individual passenger in the real evacuation process. As observed in our case study, the results from our proposed simulation model match well with the record in real full-scale certification trials. Through comparative study, it is observed that the variation of physical characteristics of passengers causes a considerable impact on the variance of evacuation time, especially when disabled passengers exist. This information would provide a very useful insight for decision makers to take account of the potential perturbation of evacuation time due to the variety of passengers' physical characteristics.

However, there are several directions worth exploring in our future work.

(1) In our study, passengers are not guided by crew or evacuation signage, but move based upon distance and queue length in the evacuation process. It is therefore observed that most of the passengers escaped from Type-A exits located at the end of the cabin. In real building emergency evacuation, the building guidance played an important role in evacuation [45], it is necessary to taking the influence of the signage system or cabin crews into account [46]. The optimal design for signage system will be studied in our next work.
(2) The presence of emotion and environment factors are not considered in the present work, this factor may have an impact on the results and should be taken into account in the future.
(3) Due to the lack of real egress trial records, only four types of exits are considered in our model, it is necessary to further collect more data to broaden the applications of our model for all types of exits.
(4) As indicated by the sensitivity analysis, N_{RC} is an important parameter in our simulation model. This parameter should be carefully calibrated by conducting analogy or virtual experiments in our further work.
(5) In our study, passengers are assumed to evacuate individually. It may not be realistic because a small group of passengers with family relationship oftentimes evacuate together. Such phenomenon was seen in Manchester fire (1985) in the UK and made evacuation behaviors much more complex.

Acknowledgments

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