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An emergency aircraft evacuation simulation considering passenger overtaking and luggage retrieval

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A R T I C L E I N F O

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A B S T R A C T

The irrational behaviors of passengers due to panic and anxiety during actual evacuations are challenging to be fully controlled by the crew. These behaviors may lead to the inefficiency of actual evacuation. This research builds a cabin evacuation model considering passengers' luggage retrieval and overtaking behaviors based on cellular automata to improve the safety of aviation passengers.. The model introduces disaster levels to describe passengers' anxiety and implements the "faster-is-slower" effect. Two possible overtaking routes are proposed, and we explored the effect of overtaking and retrieving luggage. The result shows that both overtaking and luggage retrieval negatively impact evacuation efficiency, and the impact of baggage retrieving is greater than overtaking. However, overtaking can essentially eliminate the influence of baggage retrieving. The effect of prohibiting irrational behaviors in different cabin compartments is analyzed to simulate crews' guidance. The results show that the crew's enhanced guidance of the second part is the most effective.

1. Introduction

1.1. Background

Every life matters, but fortune is fickle. Disasters are often difficult to avoid completely, so evacuation is crucial as the last defense for people's lives. Previous studies suggest that a sound evacuation plan could save lives effectively [1], whether it's on a large scale like evacuation between counties [2–5], or small scales like building evacuations [6–8], ship evacuations [9,10], and aircraft cabin evacuations [11]. According to the research of The National Transportation Safety Board (NTSB), 78% of deaths happened after impact, and 95.4% in which died (injured) in the fire smoke during the cabin evacuation [12]. The Federal Aviation Administration (FAA) stipulates that any aircraft must be tested to evacuate all passengers and crews within 90 s before it can fly, which is known as 90-second certification [13], but such tests are not entirely effective at solving the problem. Because human behaviors are complicated and unmanageable during an evacuation [14,15], these behaviors have a very serious impact on the evacuation [16]. The tragic Aeroflot Flight 1492 accident in Moscow claimed 41 lives in 2019 [17], it was a severe accident. However, the video shows that passengers still left the plane with luggage in their hands, and it is widely believed that the evacuation was delayed by passengers retrieving hand luggage. These behaviors are not included in the 90 s tests but do exist in the real evacuation. This has led to some thinking and discussion: what does it mean for passengers to retrieve their luggage in evacuation? Faced with passengers' behaviors affecting evacuation, what should the airlines do to speed up the evacuation? Moreover, what should a passenger do if someone is retrieving luggage in front of him/her? These are the questions that this article needs to study.

In fact, FAA regulations prohibit carrying luggage in evacuations, but this behavior is not new. This phenomenon has again attracted attention because increasingly videos show passengers' luggage retrieval behavior in the evacuation, even in very severe disasters. As early as 1984, the Aviation Safety Board of Canada (CASB) [18] stated: "Most passengers choose the nearest exit for evacuation. Many stopped to retrieve their hand luggage before leaving" NTSB called for the researchers to study the influence of luggage for evacuation in 2018 because the evacuation was objectively delayed by luggage retrieval behavior, but due to the accident data collection is relatively difficult and the simulation of the cabin is difficult to design, the effect of luggage on the evacuation efficiency have been unable to get effective research. However, there are

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still some relevant studies on this term: Chang and Yang [19,20] concluded that luggage is an important obstacle in cabin evacuation through a questionnaire study of passengers affected by the accident of China Airlines Flight CI-120 in August 2007. Johansson [21] uses Pathfinder, FDS, Evac and other simulation methods to conduct multiple sets of simulation on Airbus A320, studying the influence of factors such as passengers' luggage and corridor width, and the fitting effect of these existing simulation methods on luggage retrieval behavior in evacuation. Johansson argues that Pathfinder is better suited for simulating the behavior of picking up luggage, but points out that both models depict passengers as rigid bodies, which means they can't move sideways between other people in tight spaces as they would in real life. And this will significantly amplify the harm of luggage retrieval. Giitsidis et al. [22, 23] built a simulator based on cellular automata, and his study considered the luggage retrieval behavior, but there is no in-depth discussion surrounding the behavior in his work, passenger's luggage retrieval behavior was simplified as a pause, and the rear passengers must wait for the pause. Lee and Lee [24] established A questionnaire for passengers' willingness to retrieve luggage and other behaviors in cabin evacuation. Based on the questionnaire, a structural equation model was established to explore passengers' desire to do these behaviors. Then Anylogic was used to conduct an evacuation simulation of the A380 cabin, her work explored the influence of passengers' behavior of picking up luggage and choosing exit. Best et al. [25] established a simulator named PED-AIR, in which passengers can pick up luggage, but the paper did not discuss the impact of passengers picking up luggage, and passengers also appear as rigid bodies.

The published researches on this issue are problematic, it is questionable to discuss passengers' luggage retrieval behavior in isolation because overtaking behavior is also common in evacuation. If the actual impact of luggage retrieval is to be studied, a discussion that goes on overtaking behavior is essential.

Overtaking behavior is a common behavior in daily life, and it has been well studied in many scenarios like merging passage of subway stations [26], unidirectional pedestrian flow [27], and narrow bottlenecks of exits [28], classrooms [29], etc. The social force model (SFM) is a popular model to simulate pedestrian flow, many studies build their model based on SFM. Shi [30] studied the effect of luggage-related facility layouts on conflict reduction among pedestrians considering overtaking behavior. Zhou et al. [31] divided passengers into three categories considering panic passengers and luggage-laden passengers, and then modified SFM to simulate the evacuation of subway stations. Fang et al. [32] used SFM to simulate the results of passengers on the evacuation of an inclined vessel and explored the effect of the tilt angle of the vessel on the evacuation result. However, the scalability of SFM is relatively poor compared with cellular automata, there are many attempts to use cellular automata to improve overtaking behavior in evacuation. Li et al. [33] built a simulator based on cellular automata considering aggressive groups' overtaking behavior and its effect, he argues that evacuation efficiency will be the highest when the proportion of aggressive groups is moderate and the degree of aggressiveness is high. Fu et al. [34] established a multi-velocity field model to study disabled and other heterogeneous individuals in evacuation, the normal pedestrian could overtake the disabled ones.

Since overtaking behavior is accompanied by differences between individuals, different types of pedestrians have also been discussed, including the elderly, the disabled [34,35], children [36], vulnerable populations [2,37], etc. On the whole, existing overtaking behavior studies mainly follow the "lane changing-speed-up-overtaking" approach. Such approaches, however, have failed to address the overtaking behavior in very narrow spaces like airplane cabins, buses, and trains. Although some studies have used questionnaires to investigate the effects of competitive behaviors like passenger overtaking in ships and airplanes [38,39], the conclusions of such surveys still require experiments or simulations to verify the consequences of these behaviors. Therefore, it is necessary to conduct targeted modeling research on overtaking behavior in such regions.

1.2. Aim and scope of the study

For narrow scenes like aircraft cabins, trains, and ships, one single passenger's irrational behavior may cause congestion in the corridor, which will significantly impact the evacuation. It is necessary to study the behaviors of similar scenes to help airplane makers evaluate the safety of the aircraft precisely, which will improve the safety of airplane passengers. But previous researchers have not treated overtaking and luggage retrieval behavior in much detail. So this study intends to study these behaviors in the aircraft cabin. What's more, passengers may do different behaviors facing different disasters, so this work will model passengers' behaviors in the evacuation of the cabin and study the effects of that. To sum up, the main objectives of this study include the following:

(1) Design luggage retrieval behavior and overtaking behavior model considering the disaster in view of the cabin environment.
(2) Build a simulator to simulate these behaviors since conventional simulation softwares, such as Netlogo, AnyLogic, and Pathfinder, are difficult to reproduce the behavior of similar scenes.
(3) Study the influence of passengers' behavior under different disaster levels.

The rest of this paper is organized as follows. Section 2 introduces the basic rule/the simulator of this model, and some basic parameters are presented in Section 2. Section 3 introduces how passengers' samples are produced, the rules of passengers' behaviors, and a flowchart of the evacuation from the view of a passenger will be given. In Section 4, we will discuss how the calibration of the model has been performed. Section 5 use A320 as an example to analyze the sensitivity of some parameters in the model, and we will make a comparison of simulation results between the model and the traditional models. Section 6 summarizes the conclusions of this study.

2. The proposed model for the simulator

Since two-aisle planes have more routing possibilities, the effection caused by passengers' congestion may not be significant enough. A320 is a representative of the narrow-body aircraft and this article will take it as an example to introduce the model, and the results will also be presented using it. However, this model focus on passengers' behaviors, and the simulation scene can be changed easily, which means this model is extensible for many types of aircraft.

Under the 90-second certification requirements, only half of the exits are opened [40]. The parameter settings for A320 in this simulation are presented in Table 1.

FAA defined nine types of exits for passenger aircrafts with heights in the range of 0.48 and 1.83 m(see 14 CFR 25.807), but seven types of exits are often used in the real evacuation. The size of these exits will influence the exit flow rate significantly, and exit flow rate is an important parameter in the evacuation because it is the main bottleneck of the evacuation. Different exits often have different flow rates, and smaller exits have lower flow rates. The list of several exits types and

Table 1
The parameters setting of the simulation model [41].

parameters	value
number of seats	152
number of aisles	1
seat pitch	29 in
seat width	18 in
aisle width	19 in
overwing exits	2 Type-III exit
passenger doors	2 Type-A exit

their flow rates is tabulated in Table 2.

These types of exits can be divided into two categories, the floor level exits(Type-A, Type-B, and Type-C) are the main exits in the boarding or deplane, these exits are opened by the crew in the real evacuation, the overwing exits(Type-I, Type-II, Type-III) are located in the middle of the airplane, and these exits are often opened by the passengers near the exits.

2.1. Discretization of space

As is mentioned in the introduction, compared with the evacuation of buildings and squares, the cabin has a more narrow space and a higher density of evacuated people. Hence the aircraft evacuation model has higher requirements for accuracy. Some past models used 0.4 × 0.4 m node [43,44], and each node can only accommodate one person, but these models are a bit rough by ignoring the actual difference in the size of the cabin space. Some models use a grid of 0.1 × 0.1 to describe the cabin more finely [45]. However, such models have the disadvantage of slower calculation, which is not conducive to repeated experiments and generate statistical results. Therefore, our work discrete the space in to 4 types of cells with different size, the attributes of these cells are tabulated in Table 3 and Fig. 1.

Four different cells are presented in Fig. 1, the barrier cells include the seats and the walls, passengers can not get into these cells. The seat area cells are for the space between seats, in which passengers can move, but their speed will be reduced to approximately 68%. The aisle cell-1 and aisle cell-2 all represent the space in the aisle, but the aisle cell-2 is smaller, it's width is as long as the seat area cells. Passengers will not be slowed down as they move through these aisle cells.

2.2. Passengers movement rules

(1) Floor field

Passengers' goals are highly certain in the emergency evacuation, and the route is restricted. So in this work, we assumed that passengers would select the cell with the lowest floor field. In order to meet passengers' need of retrieving luggage, two floor fields are presented, and they are shown in Fig. 2:

1 Exit floor field, the value in the floor field is the number of cells separated from the exit, and passengers will strictly follow the maximum floor field gradient to the exit under the influence of this field.
2 Luggage floor field, the value in the floor field is the number of cells separated from the luggage, and passengers will strictly follow the maximum floor field gradient to the exit under the influence of this field.

(1) Update order

The main goal of the passenger is to go to the exit, sequential update along the rising direction of the floor field gradient, which means the passengers closer to the exit will be updated first. At each step of the update, passengers' speed will also be fixed according to their location and status.

(1) Conflicts

Table 2
The average flow rate of each type of exits [42].

Types of exits	Type-A	Type-C	Type-I	Type-III
Average flow rate(s/person)	0.475	0.937	1.282	1.565
Exit opening time(s)	2.25	2.25	4.61	5.295

Table 3
Celluar types and properties.

Nomenclature	Length	Width	Maximum number of passengers	Speed correction factor
Barrier cells	–	–	0	–
Seat area cell	0.46	0.15	1	0.68
Aisle cell 1	0.48	0.65	3	1
Aisle cell 2	0.48	0.15	2	1

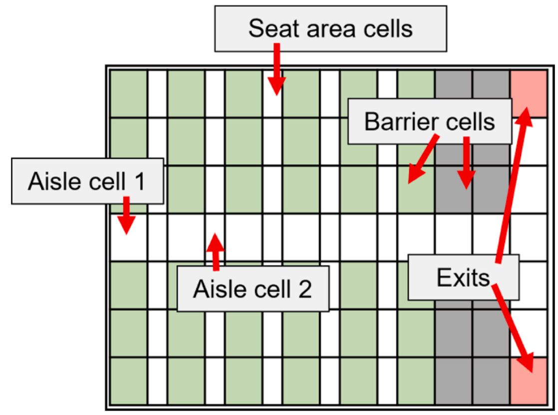
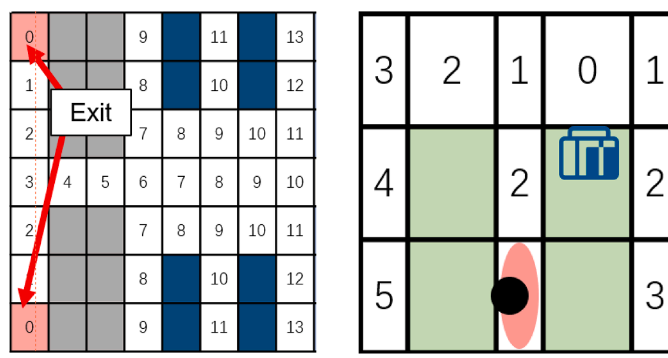


Fig. 1. Celluar types.



(a)Exit floor field (b) Luggage floor field

Fig. 2. Two Floor Fields in evacuation.

If multiple passengers want to enter the same node simultaneously, conflicts will occur. The conflict resolution depends on the speed of passengers: passengers with a higher speed will have a higher chance (i. e., the probability is the ratio of the speed of each passenger) to enter the node.

(1) Movement rules

Human movement in real life is continuous, but the cellular automata model is discrete. The movement of passengers from cell to cell often depends on the comparison between the distance walked by passengers in the cell and the length of the cell. The accuracy of this way depends on the discretization of time. For example, when the cell length is 0.53 m and time is divided in seconds, the passenger of 0.18 m/s speed and passenger of 0.25 m/s all require 3 s to leave, but if time is divided in 1/10 s, the former needs 3.0 s and the latter only needs 2.2 s.

Improper discretization of time will cause a waste of moving speed, resulting in distortion of the simulation. To solve this problem, previous models have made many efforts: Fang et al. [45] used a finer-grid model to improve accuracy, but a tremendous computational burden is unavoidable, Liu let every passenger takes a time unit to complete his movement, and sum them up as total evacuation time(TET). In order to achieve a balance of accuracy and computing burden, this work set tolerance for each cell, and when the distance walked by a passenger in the cell reaches the cell length plus/minus tolerance, the passenger will be regarded as entering the cell. However, the difference value between the actual distance and the cell length will still be counted in the next cell, and the passenger needs to complement the difference in the next step.

3. The behavior model

3.1. Retrieving luggage

Passengers often choose to take expensive luggage on the airplane, and airlines also recommend passengers to carry valuables, and that is why passengers are likely to insist on retrieving their luggage in evacuation. Passengers' luggage is often distributed on the overhead luggage bin near the passenger seat. In this work, passengers' luggage will be randomly generated in the cell corresponding to the passenger seat or within two cells next to the passenger seat. A luggage floor field is generated with baggage, as shown in Fig. 2(b). Passengers will go to the luggage location to pick up their luggage under the action of the venue.

As shown in Fig. 3(a), passengers in the model will be abstracted as ellipses, the length and the width of the ellipses will be settled by their anthropometry. when passengers pick up their luggage, they inevitably face the luggage rack, which is conducive for the passengers behind to overtaking them.

As shown in Fig. 3(b), after taking the baggage, the passengers' speed and their size will have a corresponding change, passengers' luggage is usually placed around or back behind him/her, so in the simulation, the passenger's luggage will increase in passengers' size by increasing the length or the width of the ellipse.

3.2. Overtaking behavior

Fig. 4 shows the size scale of pedestrians, the aisle, and seats in the A320 cabin. A pedestrian in the aisle can feel free to move around even if his body keeps focusing forward, and there is still some room (approximately 5.5 inches), this does not seem to be enough for other pedestrians to pass. Still, overtaking can often be seen even in deplane processing. That is partly due to passengers generally choosing to give way to the passengers who want to surpass when it is not urgent, and partly, passengers being overtaken can be pushed aside.

From some videos of the 90 s certification [46], we can see that passengers are not nervous, and the overtaking is rare because they know there is no actual danger. However, in actual evacuation, overtaking, crowding, and seat climbing are all common behaviors. So this work introduces the anxiety coefficient$m$as a description of passenger anxiety, which can be the motivation for them to overtake the slower ones.

$$m = Ct_{wait}^{\delta} \tag{1}$$

where C present passengers' character, t_{wait} is the waiting time since the front passenger stagnate, δ is the level of disaster, passengers' character is assumed to divide into three categories: mild, neutral, and aggressive, and it is evaluated by

$$C = \begin{cases} 0 & mild \\ 0.5 & neutral \\ 1 & aggressive \end{cases} \tag{2}$$

It is assumed that passengers with a mild character will not overtake the passengers in front, and passengers with neutral and aggressive personalities may have different degrees of this tendency.

This work assumes passenger's anxiety is related to the passenger's waiting time and the disaster situation. The more serious the disaster, the more passengers will want to leave faster. Based on the above assumptions, we can find two points:

(1) When t_{wait} equals 0, the passenger's anxiety should be 0.
(2) When δ equals 0, the passenger's anxiety only increased slightly with time.

Considering the above factors, the second part of the formula is t_{wait}^{δ}. In order to control the parameter range, this work generated passenger anxiety coefficient distribution through repeated experiments to standardize the data by z-score method, to prevent outliers from causing errors beyond the known distribution, this work set $t_{wait}^{\delta} \in [0, 2]$. This work establishes the anxiety threshold M as an input parameter, and it is assumed that passengers will overtake the passenger ahead when $m > M$.

The passenger's overtaking rules are as follows:

R1: When the passenger feels anxious (i.e. $m > M$), he/she will be possible to overtake the passenger ahead every second(probability). When m reaches 1.9, the passenger will be possible to crowd the cell, which is already crowded with two passengers(probability). This behavior will cause the cell to deadlock, which means the three passengers in the cell all stagnate for 0.5 s.
R2: The value of the anxiety coefficient affects passengers' expected speed; passengers will overtake when they are dissatisfied with the speed of the passenger aheadv_{front}, the passenger i will speed up when he/she feels anxious, and his/her speed will be fixed by$v_i = v_i \times m$, and m is the first part of $f_{overtaking}$.
R3: Passengers will have two routes to overtake, which are R3-1 and R3-2, respectively:

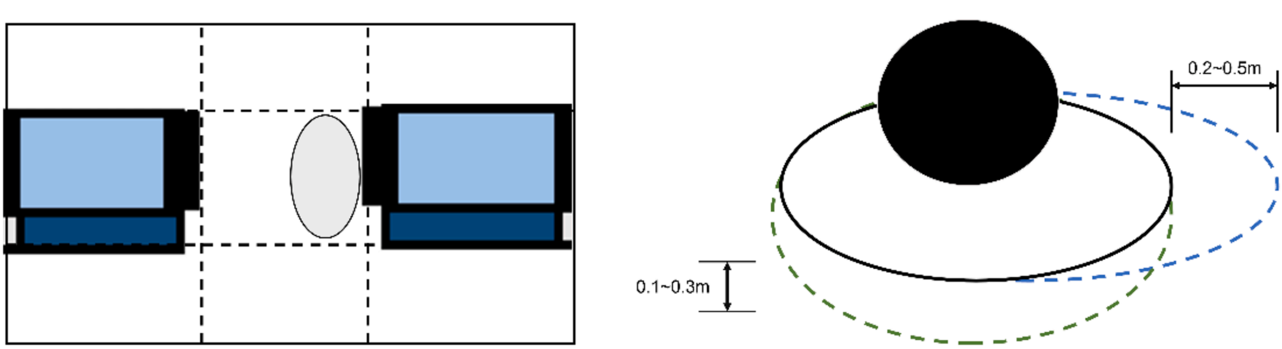


Fig. 3. Schematic diagram of passengers' luggage retriving behavior.

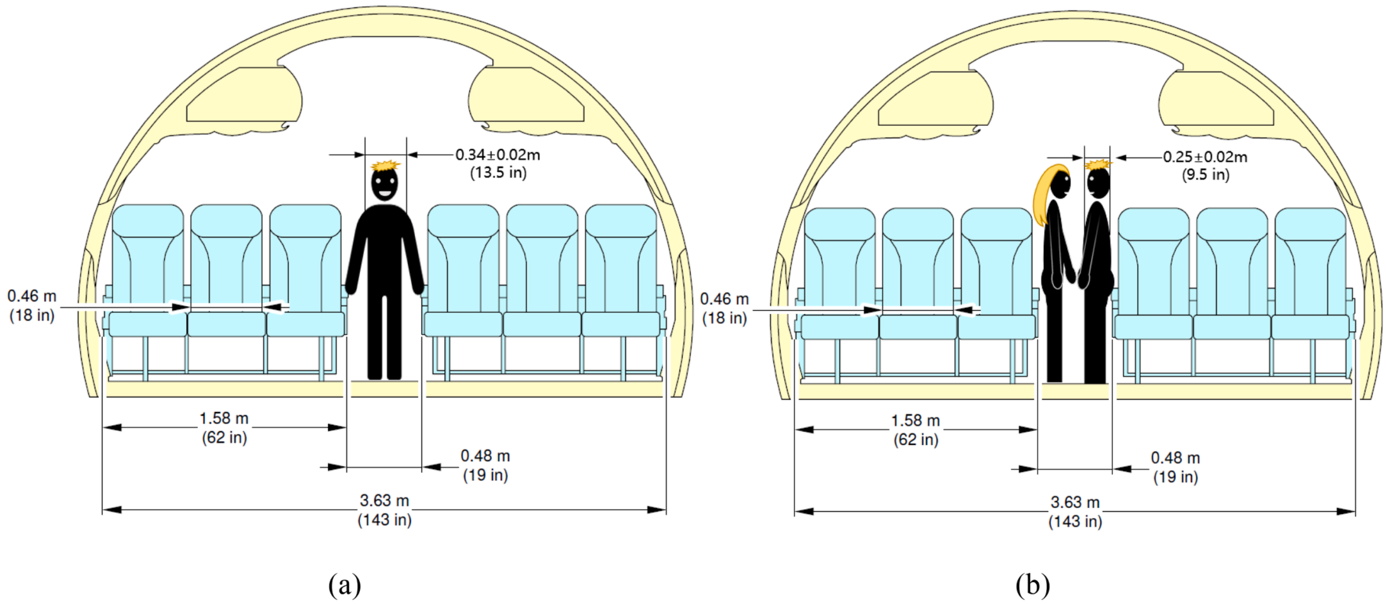


Fig. 4. A320 cabin-pedestrian size scale drawing.

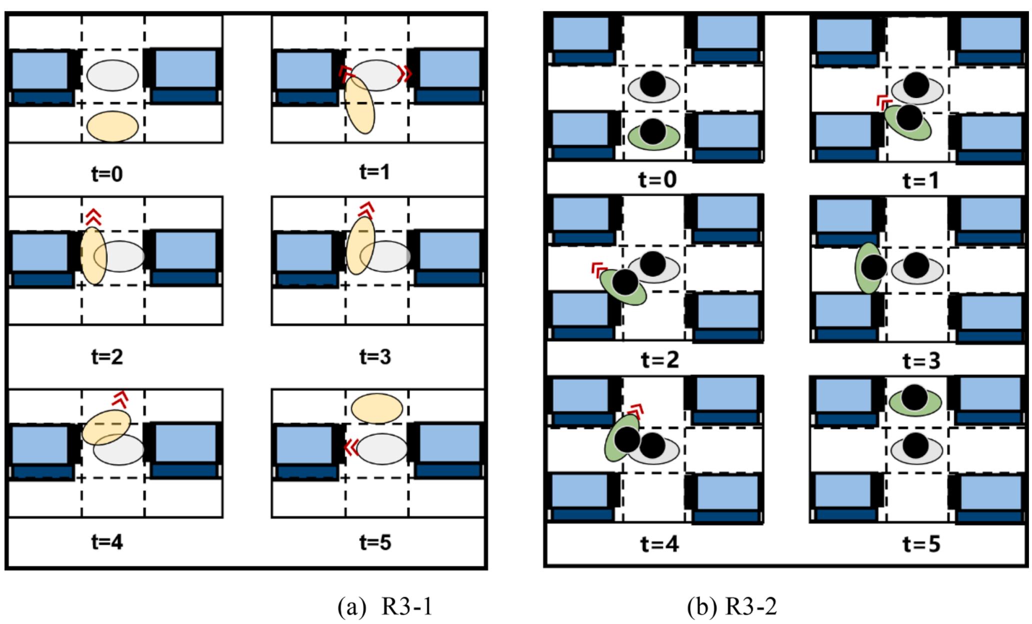


Fig. 5. Two overtaking routes in a narrow aisle.

R3-1: Passengers will choose this route shown in Fig. 5(a) when there is no space on both sides of the passenger being overtaken(POB) or when the POB retrieves luggage. When choosing this route, passengers will not leave the main aisle but directly crowded and overtake sideways. The body of the passenger i is represented by ellipse i, the area of which is S_i. These ellipses can overlap each other due to the elasticity of the human body. However, the overlapping part will cause friction related to the overlap area S_{ij}, representing the overlapping part of passenger$i$ and passenger$j$. S_{ij} will slow both passenger$i$ and passenger$j$ down, the degree of the slow effect of passenger i is $\frac{S_{ij}}{S_i}$, and that is the second part of $f_{overtaking}$. Passenger will keep moving until half of the passenger's body exceeds the passenger ahead while $v_i > v_{front}$, if $v_i \leq v_{front}$ in that process, the overtaking fails; Considering the elasticity of the human body is limited, when the overlapping area beyond 20% of the passenger's area, the overtaking fails as well, to sum up, $f_{overtaking} = m\frac{S_{ij}}{S_i}$.

R3-2: This route shown in Fig. 5(b) uses the gap between the seats to improve the success rate of overtaking. This route can only be chosen when there is an empty seat on the sides of the POB. This route is divided into two subsections and allows passengers to select target cells in Moore neighborhoods, and firstly passengers will move into the seat area cell and then go to the main aisle cell. This route avoids frontal collisions with passengers ahead, so its success rate is higher than R3-1, but compare to R3-1, it takes a longer time.

R4: Passengers will not go to the higher cell in the floor field except for luggage retrieval. Therefore, if the passenger fails to overtake, he will remain in the overtaking position until the target cell is vacant. If the passenger overtakes success, The passenger will set the target cell to the target cell of the POB. Otherwise, the passenger will reach the current cell of POB.

3.3. The flowchart of the evacuation

Fig. 6 is a flowchart of passenger behavior during the evacuation process, where TC is the target cell. As shown in Fig. 6, passengers will decide whether to retrieve luggage or not and then go to the exit as soon as possible after the seatbelt release.

4. The calibration of the model parameters

4.1. Passengers proportion

In order to fit the actual evacuation, the sample of passengers in the evacuation should meet certain requirements to achieve a statistically significant result. According to the requirements [40] of the 90 s verification, the characteristic distribution of passengers includes the following requirements: at least 40% female; at least 35% of passengers must be over 50 years of age, and 15% of passengers must be female and over 50 years of age. However, such distribution is inauthentic for the real situation, so we adjusted it according to AASK V4.0, in which the average age of female passengers is 39.9 years, and the average age of male passengers is 40.8 years old.

4.2. Passengers' anthropometric data

Existing researches show that the main factors that may affect the evacuation include passenger's waist circumference, height, and leg length, these factors could affect the leaving time of passengers', Melis et al. [47] argues that passengers' BMI should also be considered in it. Based on the discussion in 4.1, this study will generate passenger samples according to the gender and age distributions, and then passengers anthropometric data of passengers will be generated according to the method used in the references below, and the final anthropometric factors used in the simulation include: Passenger's age and sex [14], height and weight [48], chest depth and shoulder width [49], and passengers' leg length [50].

4.3. Passengers' speed data

The speed of passengers is restricted in the cabin, and the physiological limitations of personnel are not yet reached. Therefore, this article's setting of personnel speed is based on the distribution of a cabin evacuation experiment [51], as shown in Table 4, which presents that passengers' speed is not related to human physiological factors but related to luggage.

According to Table 4, passengers' real-time speed can be expressed as

$$v_i = v_{i0} \times f_{luggage} \times f_{overtaking} \times f_{disaster} \times f_{location} \tag{3}$$

Where v_{i0} is the initial speed of passenger i, values from Table 4, $f_{luggage}$, $f_{overtaking}$, $f_{disaster}$ and $f_{location}$ are speed correction factors affected by luggage, overtaking, disaster and the location of the passenger i, The level of disaster δ take the value in (0,1,2), represents three levels of disasters, respectively.

$$f_{luggage} = \begin{cases} 0.92 & Luggage \\ 1 & NoLuggage \end{cases} \tag{4}$$

Table 4
Passengers' combined Ailse Movement [51].

		Luggage	No luggage
Aisle Speed(m/s)	average(sd, N) median[min-max]	0.52(0.14,92) 0.49[0.27–0.93]	0.56(*0.14,93) 0.53[0.28–0.97]

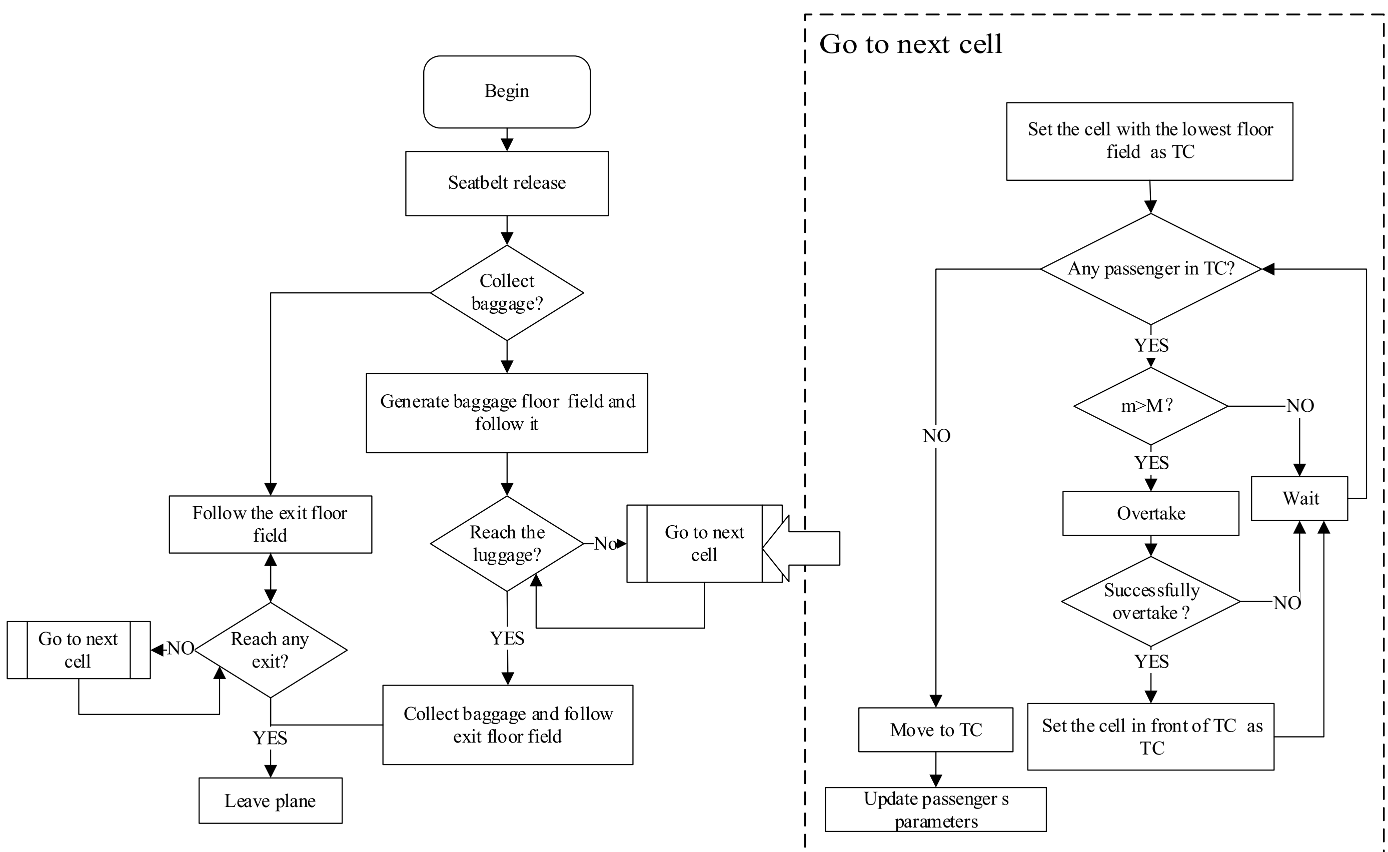


Fig. 6. The flowchart of the evacuation.

$$f_{disaster} = \begin{cases} 1 & \delta = 0 \\ 1.1 & \delta = 1 \\ 1.2 & \delta = 2 \end{cases} \tag{5}$$

$f_{location}$ Values form Table 3 and $f_{overtaking}$ values from chapter 3.2.

After forming the basic simulator, we compared the time of passengers in the test simulation with the experimental data [35], and we did a t-Test with them, the p-value is 0.167, confirming that the existing anthropometric data and movement correction data are reasonable and effective.

4.4. Passengers' behavior time

In a complete cycle of evacuation, evacuation starts by unbuckling the seatbelt, seatbelt difficulty is not considered in this model, but we set a time for passengers to unbuckle their seatbelt. The luggage retrieval time and average leave seat time are use to calibrate the model, and their data are shown in Table 5 and Fig. 7

5. Case study

5.1. Evacuation simulation for Airbus A320

Based on the proposed model, we developed a simulation program with python. Fig. 8 is a step snapshot of a simulation process. As shown in Fig. 6, passengers retrieving luggage stop some passengers from moving forward, but some passengers chose to overtake them. The green ones represent passengers retrieving luggage, the gray ones represent passengers overtaking by route 1, the yellow ones represent passengers overtaking by route 2, and the red ones represent passengers not doing irrational behaviors.

5.2. Sensitivity analysis

This section will focus on different passenger behavior and the combination of qualitative influence. Total Evacuation Time(TET) and the Personal Evacuation Time (PET) are important results for an evacuation, we will analysis these behaviors' influence on TET and PET in this section.

5.2.1. Sensitivity of anxiety threshold M

This work sets 100 experiments for M from 0 to 2 to test the impact of anxiety threshold Mon evacuation, Mincreases by 0.02 in each experiment, $\delta = 2$, each experiment repeats 50 times and averaged. The result is shown in Fig. 9. From Fig. 9, we can see the change of average TET, in the interval of $M < 1$, although $m > M$ is easier to achieve. Still, passengers' speed is slower because of the influence of m($v_i < v_{front}$), the overtaking has been judged a failure before it has even begun, so TET does not change much; in the interval of $1 < M < 1.6$, TET increases with M, and in the interval of $1.6 < M < 1.9$, TET decreases with M. The change in TET could be change with the overtaking behavior ratio in these two intervals. However, TET increases much in the interval of 1.9 $< M < 2$, that is because the passengers' overtaking will all lead to deadlocks in the interval, resulting in a significant increase in TET.

Table 5
Parameters setting for different scenarios [51].

	Seat Pitch (inches)		
	29	31	33
Avg. Bag Retrive Time (s)	5.1(1.5,60) 4.8[2.8–9.3]	4.5(1.4,64) 4.3[2.4–9.2]	3.9(1.0,61) 3.8[2.2–6.9]
Avg. Seatbelt Unfasten Time (s)	1.9(0.7,60) 1.8[1.0–5.4]	1.9(0.6,64) 1.8[1.0–4.3]	1.8(0.5,61) 1.8[0.9–3.4]
Avg. Leave Seat Time (s)	2.6(1.0,60) 2.4[1.1–6.4]	2.5(1.4,64) 2.2[1.0–11.7]	2.2(0.8,61) 2.0[1.0–4.1]

5.2.2. Sensitivity of disaster level δ

This work sets three experiments for δ from 0 to 2 to test the impact of disaster levels δ on evacuation, δ increasing by 1 in each experiment, and $M = 1.5$. Each experiment was repeated 500 times, and the result is shown in Fig. 10.

As shown in Fig. 10, by comparing experiments of $\delta = 1$ one and $\delta = 0$ one, the average TET decreases by δ because passengers are faster when δ increases; while the standard deviation increases because more passengers choose to overtake when δ increases. However, even though passengers have the fastest speed, as shown in, the average of TET in the experiment of $delta = 3$ is longer than else, which can be viewed as the "faster-is-slower" effect.

5.3. Comparison of simulation results between the model and the traditional models

To better illustrate the effectiveness of the model, we compared the results of the three disaster levels with the existing A320 simulation models. The airExodus [52] is a classic aircraft model, which focuses on help proforming 90 s certification, the airExodus is still developing accroding to Galea, but the classic airExodus didn't consider passenger' behaviors. The VacateAir [53] takes passengers' panic, competing behavior, and the exit choices into consideration, and it consider the fire hazards. Etisa [54] is an agent-based computer model, and it also be designed to certification. As is shown in Fig. 11, The performance of our model is very close to that of the traditional model in the case of light and moderate disasters, but the results obtained in the case of heavy disasters are closer to the time observed in the actual evacuation. This shows that our model has good compatibility and better performance at the heavy disaster level.

5.4. The application of the model

So far, the two sides of overtaking are presented: It may delay the evacuation time when there are no stagnant passengers or ultra-low speed passengers, but overtaking is conducive to the rapid evacuation when there are such passengers.

However, whether this phenomenon uniform throughout the cabin is still worthy of inquiry. It is difficult for crews to guarantee that every passenger will not retrieve their luggage or crowding in actual evacuation. However, these are not uncontrollable behaviors, and if the crew can reasonably guide the behavior of passengers, evacuation efficiency will be further improved. However, the coverage area of the crew is limited. In order to maximize the guiding role of the crew, this work divides the cabin into five parts, as shown in Fig. 11, and separately prohibits luggage retrieval behaviors in the five parts.

In the actual aircraft evacuation, the cabin is not always full. Three cases are set up to study the impact of these two behaviors on passengers of different counts. These cases are all simulated based on the A320 cabin and have the same parameter settings.:$M = 1.5$, $\delta = 1$, and $L = 0.5$. However, the total numbers of passengers are 152 for case 1, 114 for case 2, and 76 for case3. The method of randomly distributing seats is used to express the requirements for maintaining cabin balance in the cabin. In each set of cases, seven sets of experiments are set up: the prohibition of overtaking and retrieving luggage in each part and control groups. The former number represents passengers' count condition, and the latter number represents the part prohibiting irrational behaviors(e.g., case1–3 represents 152 passengers and passengers in the third part of the aircraft are prohibited from retrieving luggage or overtaking). Moreover, two control groups are set: the subcases end with "A" represent the subcases prohibiting all passengers from overtaking and retrieving luggage, while the control groups end with "N" means no prohibition in these subcases, each subcase repeat 300 times, and the result is shown in Fig. 12.

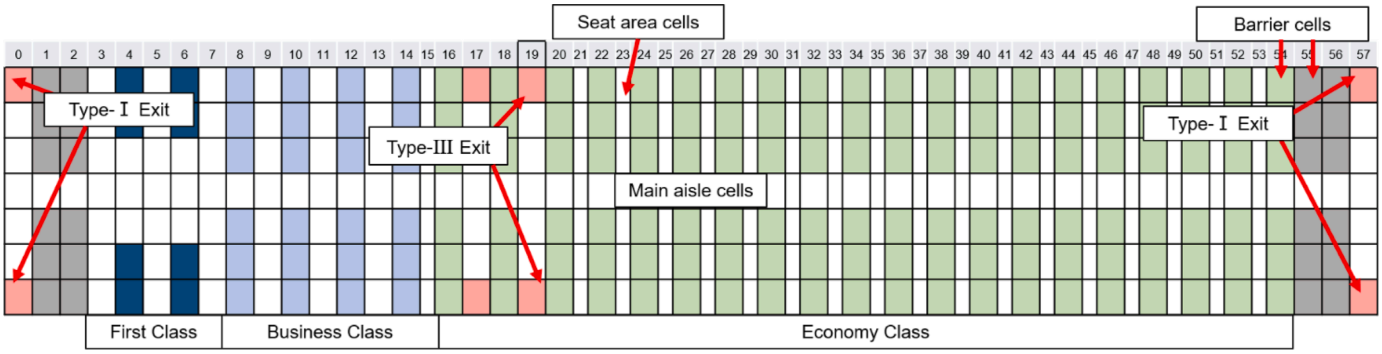


Fig. 7. The proposed discretization of A320.

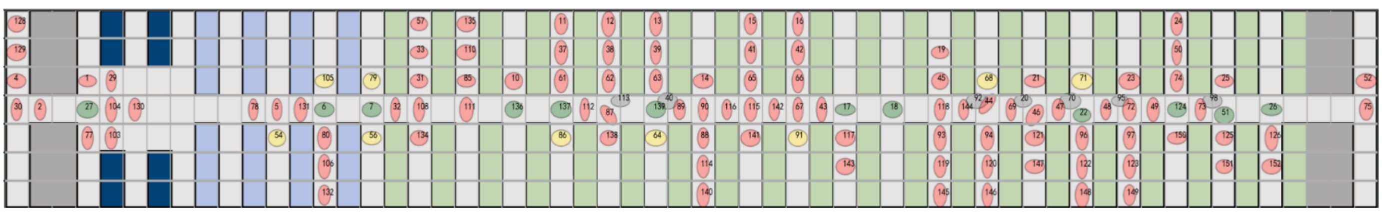


Fig. 8. A step snapshot of a simulation process.

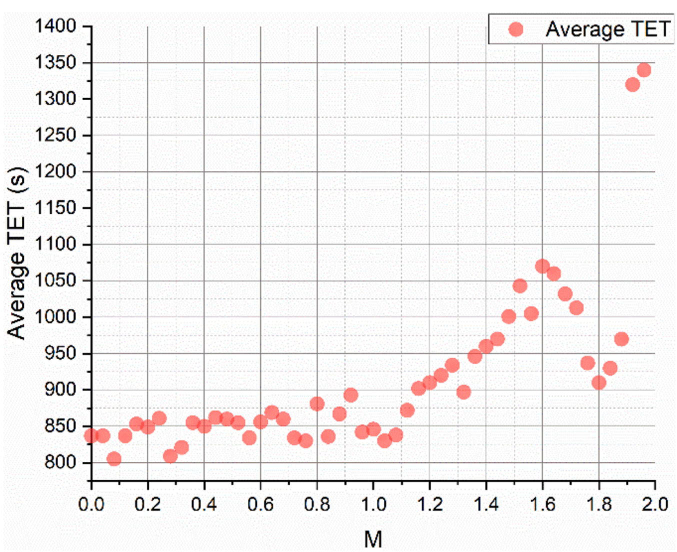


Fig. 9. Sensitivity of anxiety threshold *M*.

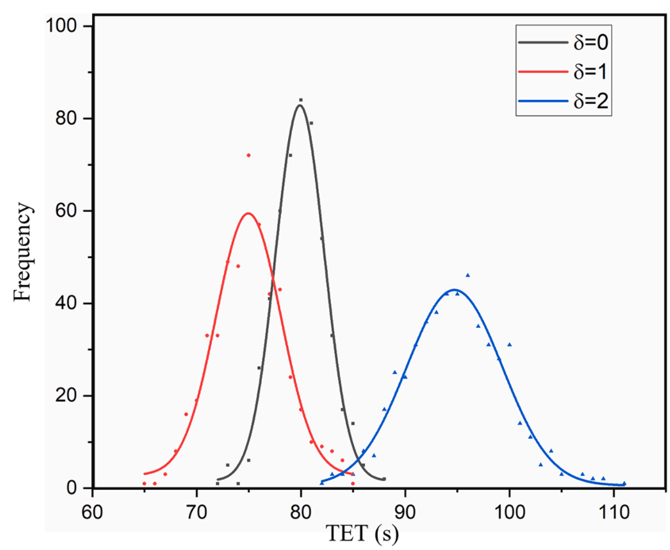


Fig. 10. Sensitivity of disaster level δ.

As shown in Fig. 12, the evacuation effect is best when overtaking behavior and baggage claim behavior are prohibited for all cabins. However, due to the limited crew, such a requirement is difficult to achieve. In order to find the different effects on the control' effects of different parts, we set the subcase with "N" as the control subcase in each case and compare each subcase in the case with the control subcase results are shown in Table 6.

In each case, we underline the two most significant subcases against the control subcase except for the subcases ending with "A" in Table 6. Subcases end with 2 and 5 are included in every case, which means the control of part 2 and part 5 is most efficient in these conditions. However, the control effects are still different, compare to CASE1 and CASE 3, the average TET of CASE1-2 is 5.3% less than CASE1-N; while that in CASE 3-2 and CASE3-N is 2.34%. Surprisingly, the control effect of CASE2-2 is the most significant one in 3 cases, which decreases the average TET by 9.9% than CASE2-N, meaning that for most of the evacuation, the controlling of part2 works best.

We also observed an interesting phenomenon from Table 6, the sum of the decrease percentage of each subcase is not always equal to the decrease percentage of the subcases ending with "A", especially in CASE3. The control of these subcases produces a minimal effect. In contrast, the control of the whole cabin performs well. To figure out the reason, we double-check the evacuation, and the reason may be passengers' cross-part movement when they try to retrieve their luggage, which delays passengers in more than one part.

What is more, Fig. 12 shows that the distributions of most subcases drag a long tail, which the crowing deadlock may cause; however, the control of part 2 could reduce this condition effectively.

The control of these two behaviors does not seem very significant for other cabins, which means that the crew should focus on guiding passengers in part 2 as much as possible and prohibiting their overtaking and baggage claim behaviors from achieving the optimal evacuation

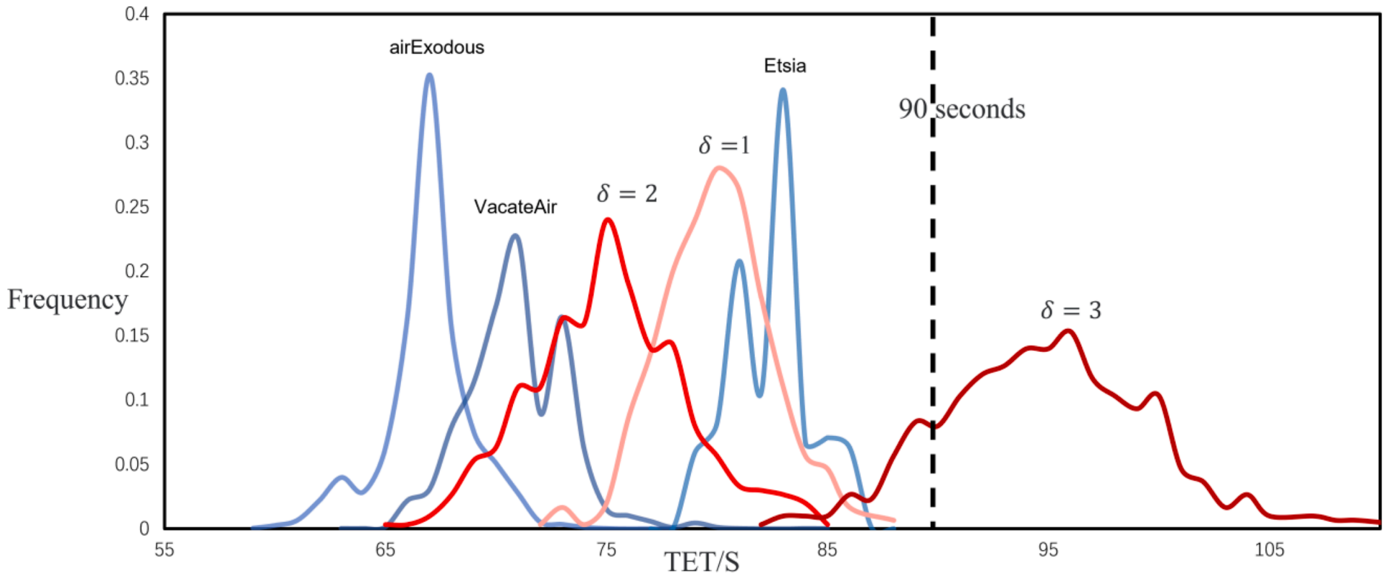


Fig. 11. Comparison of simulation results between the model and the traditional models.

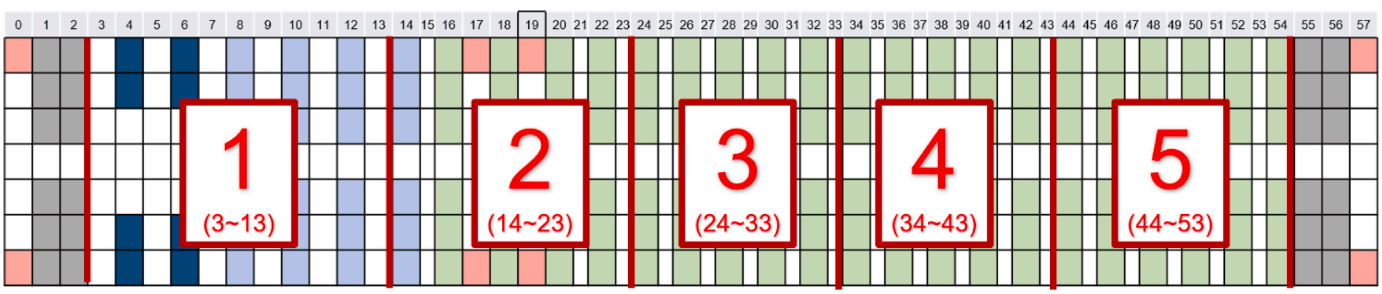


Fig. 12. Compartments Setting of Cabin.

Table 6
Results from the t-Test: two-sample assuming unequal variances for each subcase against the subcase end with "N" in each case.

	mean TET	Max TET	Min TET	Standard error	Decrease percentage(%)	t-value	p-value	95% confidence interval	
CASE1-A	66.045*	73	62	1.867	22.205	43.898	0.000	18.007	19.696
CASE1–1	83.719	110	68	7.033	1.386	2.071	0.039	0.061	2.294
CASE1–2	80.155*	95	65	5.995	5.585	8.917	0.000	3.698	5.787
CASE1–3	83.198*	106	71	6.909	2.000	3.005	0.003	0.589	2.810
CASE1–4	84.716	110	72	6.770	0.212	0.332	0.748	−0.922	1.283
CASE1–5	81.704*	104	69	7.043	3.760	5.611	0.000	2.075	4.310
CASE1-N	84.896	113	70	7.342	–	–	–	–	–
CASE2-A	51.433*	60	46	2.268	25.782	38.646	0.000	15.059	16.674
CASE2–1	64.824*	84	52	5.374	6.460	4.650	0.000	1.330	3.276
CASE2–2	62.436*	76	51	5.909	9.904	9.561	0.000	3.865	5.863
CASE2–3	63.170*	85	54	5.211	8.846	8.516	0.000	3.178	5.083
CASE2–4	67.409	85	53	6.578	2.729	−0.205	0.838	−1.156	0.938
CASE2–5	62.427*	85	54	5.979	9.917	9.618	0.000	3.878	5.868
CASE2-N	67.300	84	55	6.886	–	–	–	–	–
CASE3-A	36.833*	43	32	2.502	14.633	37.834	0.000	9.614	10.667
CASE3–1	46.824	60	38	4.132	0.216	0.463	0.643	−0.486	0.785
CASE3–2	45.352 *	70	36	5.107	2.341	4.465	0.000	0.909	2.336
CASE3–3	47.085	70	38	4.688	−0.160	−3.200	0.749	−0.790	0.568
CASE3–4	47.721	62	36	4.635	−1.078	−2.175	0.030	−1.422	−0.073
CASE3–5	44.779*	62	36	4.369	3.168	6.581	0.000	1.540	2.850
CASE3-N	46.974	64	39	4.042	–	–	–	–	–

Note: (*)$p < 0.01$, () the two most significant subcases.

efficiency. The guidance of passengers in other cabins can be relaxed to a certain extent to strengthen the guidance and control of part 2 Fig. 13.

6. Conclusion

This article presents a cabin evacuation model considering the physical characteristics of passengers, luggage retrieval, and overtaking behavior. The model conducts a targeted study on passengers'

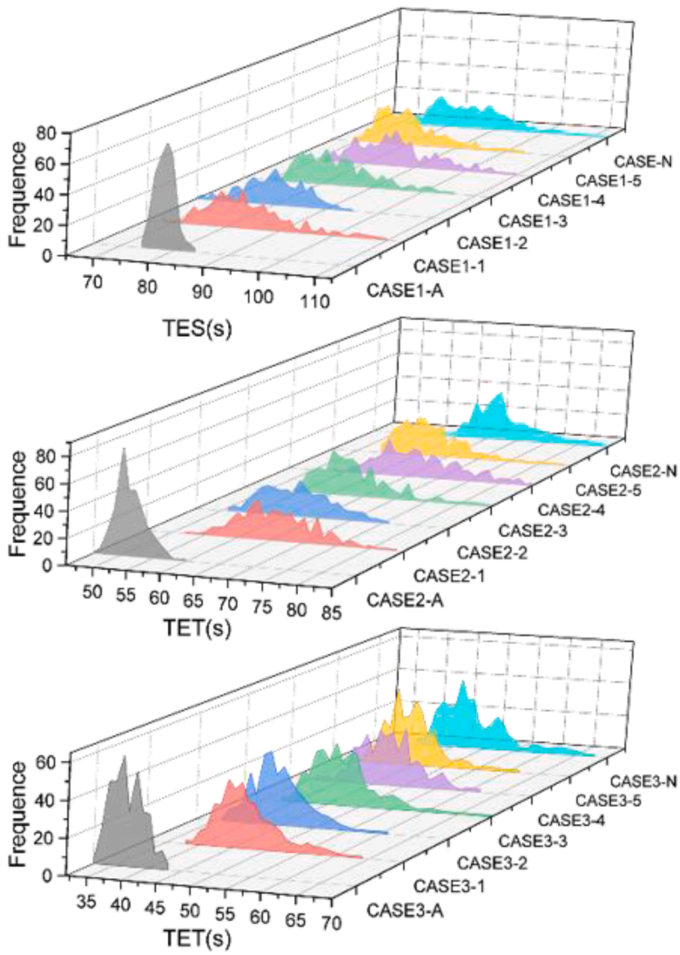


Fig. 13. Distribution of results on prohibiting irrational behaviors on different compartments of cabin.

overtaking and luggage retrieval aimed at the unique environment in the cabin evacuation. In order to study the impact of passengers' baggage picking behavior on evacuation appropriately and improve the safety of passengers, we made the following contributions:

(1) We built a simulator, which abstracts passengers as ellipses, and this simulator can simulate the size changed after the passengers take luggage, this change can affect their overtaking behavior, a similar approach can also be seen in the literature [30], but the effect is more pronounced in the aircraft cabin, especially when overtaking occurs.
(2) We modeled passengers' overtaking behavior for aircraft cabins, this behavior will be affected by passengers anthropometry and passengers' aggressiveness, and their aggressiveness will be affected by the level of disasters. We consider 3 levels of disasters, and studied their behavior in these disasters, the results and the comparison with the traditional models show that the model hava good scalability.
(3) We take luggage-retrieval behavior and overtaking behavior, and silumated the behavior of passengers under different disasters. The result shows that the overtaking behavior and the luggage-retrieval behavior will both cause negative effects in evacuation, and the luggage-retrieval behavior is worse, but appropriate overtaking behavior can alleviate the negative impact of passengers' luggage-retrieval behavior.
(4) We divided the cabin into five compartments, respectively discussed the influence of these behaviors in these compartments, and concluded that control compartments 2 and 5 had the best effect. This result may provide help for the crew in evacuation guidance.

However, there are still several possible directions in the future:

(1) In this study, the crew did not act as an objective existence. The crew's actions during the evacuation will be further optimized in follow-up research.
(2) In this model, passenger anxiety coefficients M and m are proposed to explain the passenger's overtaking behavior, but the description is rough and has not been validated. The research would have been more relevant if we could do an experiment or a questionnaire.
(3) Some parameters in the overtaking behavior need to be further experimented. Currently, we use the judgment method of overlap area and moving speed, but it may be more appropriate to use force to discuss the overtaking behavior.

CRediT authorship contribution statement

Chengcheng Song: Data curation, Methodology, Software, Writing – original draft, Validation, Investigation, Formal analysis, Visualization, Funding acquisition, Writing – review & editing. **Quan Shao:** Conceptualization, Investigation, Funding acquisition, Resources, Supervision. **Pei Zhu:** Supervision. **Min Dong:** Supervision. **Wenfei Yu:** Supervision, Writing – review & editing.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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