Int j simul model 21 (2022) 2, 261-272
Original scientific paper

SIMULATION OF AIRCRAFT CABIN EVACUATION STRATEGY BASED ON EXIT FLOW EQUILIBRIUM

Guo, X. Y.*; Zeng, Z.**; Li, M. X.***,# & Fu, S.*
* School of Civil Aviation, Zhengzhou University of Aeronautics, Zhengzhou, 450046, China
** School of Management Engineering, Zhengzhou University of Aeronautics, Zhengzhou, 450046, China
*** School of Safety Science and Emergency Management, Wuhan University of Technology, Wuhan, 430070, China
E-Mail: lmx@whut.edu.cn (# Corresponding author)

Abstract
Exit flow equilibrium method based on crowd evacuation dynamics theory was applied in this study to clarify the reasons that hinder the evacuation of aircraft cabin passengers as well as reduce the evacuation time using the A-configuration cabin layout of a B737-800 as an example. Pathfinder simulation software was utilized to simulate and compare the evacuation efficiency of three scenarios: no command scenario, exit equilibrium scenario, and evacuation sequence arrangement; reveal the key reasons causing the evacuation congestion of aircraft cabin; and propose the evacuation strategy with the minimum amount of time. Results show that the evacuation time is 99 s under the condition of no command and 86.8 s under the condition of balanced exit utilization. The evacuation efficiency in the case of balanced use of emergency exits reaches the maximum when passengers near the aisle are evacuated first at an evacuation time of 79.3 seconds. The obtained conclusions provide a significantly reference and method support for efficient emergency evacuation strategies of civil aircrafts.
(Received in February 2022, accepted in May 2022. This paper was with the authors 1 month for 1 revision.)

Key Words: Cabin Evacuation, Exit Flow Equalization, Evacuation Sequence, Evacuation Efficiency

1. INTRODUCTION

Aircrafts have become a common transport tool with the rapid development of air transportation. According to the International Air Transport Association (IATA), the aircraft ranks first in terms of safety, but deaths are the main indicator. Various flight unsafe incidents have also emerged in recent years due to the increase of civil aviation traffic and uncontrollable potential risks, such as bad weather and bird strikes [1]. Flight crew members will likely implement an emergency landing and evacuate passengers when a safety risk exists during the flight [2, 3]. According to the National Aviation Safety Council, 95 % of passengers can survive a plane accident. Therefore, the evacuation of passengers from the cabin within a limited amount of time is an important factor related to their safety.

Currently many countries in the emergency evacuation security verification of the airworthiness of the airplane passengers in case of an emergency evacuation time to the relevant provisions in the cabin, such as China in large aircraft of public air transport carrier operation qualification examination and approval rules that plane to land under open 50 % of the emergency exit, passengers from the plane of time should not exceed 90 s [4]. Therefore, the scientific formulation of an emergency evacuation strategy of civil aviation aircraft is a prerequisite to guaranteeing and improving the efficiency of emergency evacuation of passengers. However, previous studies on the emergency evacuation of aircraft cabin were typically carried out as cabin drill exercises. The aircraft cabin environment is a typical airtight and restricted space with narrow passages and dense obstacles. However, timing exercises are labour-intensive, expensive, and may lead to safety accidents to a certain extent during large-scale crowd evacuation drills [5]. Emergency drills are also limited by the attitude of participants toward the drill, system implementation, disaster atmosphere, skills and experience, and drill burnout [6], and may lead to poor performance of the drill and failure to reveal the movement rules of passenger evacuation in aircraft cabins in an emergency environment. Multiple aircraft cabin passenger evacuation scenarios based on the simulation technique, evacuation time, contrast of different situations, and space-time characteristics of passenger evacuation is designed in this work to address these limitations, achieve the evacuation strategy with the minimum amount of time, and improve the evacuation efficiency of the aircraft cabin in an emergency environment comprehensively.

2. STATE OF THE ART

Crowd experiment and computer modelling have been typically used in emergency evacuation studies [7]. However, the majority of experimental research methods have focused on small-scale evacuation experiments due to safety and ethical considerations by organizing movement characteristics of people in the experimental scene, exploring evacuation rules of pedestrians, and extracting evacuation movement parameters. For example, Isobe et al. [8] simulated the evacuation process of pedestrians in a smog-filled room under the condition of obstructed sight by providing a fuzzy eye mask to experimenters. The use flow of different emergency exits is analysed, and safety planning suggestions for building space are put forward. Okada et al. [9] examined the evacuation efficiency of an escalator in the two modes of static and upward movement by creating a scene experiment in which a crowd is evacuated using the escalator and pointed out that slow pedestrians seriously affect the evacuation efficiency of a crowd when the escalator is used for evacuation. The computer simulation method mainly uses mathematical modelling and computer programming to simulate the dynamics of the crowd system and calculate the movement results and evacuation time of the crowd. This method is characterized by repeatability, adjustable parameters, and early prediction as well as preferred by researchers because of its advantages over experimental methods in scope and speed. Muhammed et al. [10] adopted AI technology and intelligent algorithm to calculate the minimum amount of time for pedestrians to move to the safety exit in different locations and proposed a calculation model for rapidly finding the evacuation exit. Kim et al. [11] developed a crowd evacuation route selection model based on human organs and characteristics. Bottleneck points of different people in the evacuation route were determined and the purpose of finding the optimal evacuation route according to physical characteristics of pedestrians was determined by detecting risks and conditions of the evacuation route and the density of regional crowds. On this basis, scholars have analysed the impact of complex spatial structure and environmental barriers in the evacuation process of dense crowds on evacuation efficiency, such as escalators, stairs, thick smoke, limited vision, and evacuation bottleneck. However, these studies have mainly focused on the microperspective. Studies on induction strategies for large-scale crowd evacuation from the perspective of flow equilibrium of multiple emergency exits and the relationship between obstacle avoidance behaviour and evacuation efficiency based on pedestrian movement law are limited.

Fang et al. [12] established a civil aviation evacuation FGCAEM model for typical aircraft evacuation scenarios based on aircraft structure and personnel evacuation characteristics to simulate the aircraft cabin emergency evacuation. Wang et al. [13] used a questionnaire to survey several passengers and revealed that passengers are inclined to obey the command of crew members in emergency evacuation behaviour and willing to respond actively to and cooperate with the guidance of crew members. Burigat and Chittaro [14] proposed an aviation emergency evacuation tool based on virtual environment to show a nearly real cabin space environment and evacuation map in the virtual environment. Haghani [15] summarized the evacuation models in the field of evacuation dynamics in recent years and explored the differences of research conclusions under various experimental and simulated scenarios. Liu et al. [16] put forward an evacuation model that comprehensively considers key physical characteristics of cabin passengers, such as waist circumference, gender, age, and disability; assessed the cabin evacuation situation under the background of emergencies; and developed a set of safe evacuation routes for passengers to choose independently. Chang and Liao [17] analysed the impact of safety education on passenger evacuation behaviour by investigating the convenience of passengers at different positions for emergency exits during evacuation in terms of evacuation management planning. To sum up, evacuation strategies for confined spaces has mainly focused on the evacuation route selection and planning of passengers. However, the minimum geometric length of the evacuation path is often used as the basis for evacuation path planning, while the overall situation of the evacuation network is ignored in route selection. Hence, the congestion of passengers in the evacuation path with the minimum distance results in the bottleneck effect. Existing studies generally focus on local inducement and change of personnel behaviour to affect the evacuation process, while investigations on dynamic planning and organization of large-scale evacuation groups from a holistic perspective are lacking.

Therefore, this study focuses on outlet flow balance method and setting-induced evacuation strategy to address these limitations, realize the balanced use of aircraft cabin with many emergency exits, and design a different regional passenger evacuation order for the cabin space layout as well as use the Pathfinder software on the airplane cabin in an emergency to provide a reference for an efficient and effective aircraft cabin evacuation plan.

3. METHODOLOGY

3.1 Exit equilibrium

The transportation network contains many different origin-destination (OD) pairs due to the various starting points of travellers. The traffic flow in the road network reaches the equilibrium given that the route selection behaviour of travellers always exists. Giuseppi and Pietrabissa [18] proposed the first principle of the definition of traffic network balance under the assumption that all travellers fully understand the information of all road segments in the current traffic road network in response to this phenomenon. The path with the minimum distance is taken as the principle, and the same standard is used to calculate the impedance of all road segments to choose the path with minimum impedance. This assumption is also called determined user equilibrium (DUE) in actual traffic flow distribution.

For example, G is the directed graph, N is the set of left and right nodes in G, and A is the set of all road segments in G in the transportation network G (N, A). We define P as the set of all paths, R as the set of all starting points, S as the set of all key points, a as a road segment ($a \in A$), k as a path ($k \in P$), r as a starting point ($r \in R$), and s as an end point ($s \in S$). According to the description of Wardrop's equilibrium [18], the DUE allocation for the transportation network must meet the following conditions.

$$\begin{cases} c_{rs}^{k} = u_{rs} & \left(f_{rs}^{k} > 0 \right) \\ c_{rs}^{k} \geq u_{rs} & \left(f_{rs}^{k} = 0 \right) \end{cases} \quad \forall k, r, s \tag{1}$$

where c_{rs}^{k} is the actual impedance on the k path between OD pairs (r, s) and u_{rs} is the minimum distance path impedance between OD pairs (r, s). Babicheva [19] proposed a mathematical programming model to satisfy the DUE condition as follows:

$$\min Z_{DUE}(v) = \sum_{a \in A} \int_{0}^{v_a} t_a(w) dw \tag{2}$$

where t_a is the actual impedance on road segment a with the following constraints:

$$\sum_{k\in P_{rs}} f_{rs}^{k} = q_{rs}, r \in R, s \in S \tag{3}$$

$$f_{rs}^{k} \geq 0, \quad r \in R, s \in S, k \in P_{rs} \tag{4}$$

$$v_a = \sum_{r\in R}\sum_{s\in S}\sum_{k\in P_{rs}} f_{rs}^{k}\delta_{rs}^{ak}, \quad a \in A \tag{5}$$

where f_{rs}^{k} is the flow on the k path between OD pairs (r, s), q_{rs} is the traffic demand between OD pairs (r, s), P_{rs} is the set of all paths between OD pairs (r, s), and v_a is the flow on road segment a. If a is on the k path between OD pairs (r, s), then δ_{rs}^{ak}=1; otherwise, the result is equal to 0.

The layout of the aircraft cabin and the distribution of people are comprehensively considered and an exit equilibrium algorithm is constructed on the basis of flow equilibrium theory. This method uses the evacuation time empirical formula of Togawa, given in [20], as the evaluation function and finds the optimal solution for exit choice of each pedestrian through multiple iterations. At the same time, the cabin is cut into small pieces of seat distribution units according to the space structure and specific size parameters of the cabin to form multiple small lattice areas. Accordingly, the cellular automaton method is used for the following iterative solution and path length calculation:

(1) Floyd algorithm [21] is utilized in the initial state of passengers to calculate the distance from pedestrians to each exit, and the exit with the minimum path is set as the initial value of pedestrian exit selection.

(2) According to the position of each pedestrian, the evacuation time of each exit selected by pedestrians is estimated as follows.

$$ET_j = \min_{i\in[1,n]} \left\{ \frac{Dis_{ij}}{V_j} + \frac{PED_{ij}}{F(EW_i)}\theta_{ij} \right\} \tag{6}$$

where n is the export quantity, i is the export number, j is the pedestrian number, ET_j is the estimate of the evacuation time required to select the exit i for pedestrian j, Dis_{ij} is the distance of pedestrian j from the exit i, V_j is the movement speed of pedestrian j, PED_{ij} is the number of pedestrians who precede pedestrian j on the path to exit i, F is the outlet flow rate set to 1.0 ped/m·s according to the width of the cabin emergency exit I, EW_i is the width of the exit i, and θ_{ij} is the degree of pedestrian congestion on the path from pedestrian j to the exit i that represents the large consumption of time and cost by pedestrians due to congestion in a path or gate. Many aggregations correspond to a long time spent. The following is assumed:

$$\theta_{ij} = \begin{cases} 1 & PED_{ij} \leq PED_0 \\ \dfrac{PED_{ij}}{PED_0} & PED_0 < PED_{ij} \leq 1.5PED_0 \\ 1.5 & PED_{ij} > 1.5PED_0 \end{cases} \tag{7}$$

Eq. (3) demonstrated that the time the pedestrian spends on the crowded path is 1.5 times longer than that on noncrowded paths.

(3) The estimated evacuation time of each exit selected by each pedestrian is compared, and the exit with the shortest evacuation time will be set as the exit selected by the pedestrian.

(4) Steps (3) and (4) are repeated until the results converge to obtain the final exit selection results of all pedestrians.

3.2 Scenario simulation software

The evacuation simulation software Pathfinder is a pedestrian motion simulation system developed by the American company Thunderhead Engineering. This software uses a 3D geometric space model that can be divided into a 2D planar navigation mesh, which is formed using adjacent continuous irregular triangles. Obstacles are accurately represented as gap in this navigation mesh; hence, pedestrians move in this navigation mesh space. Obstacles are accurately represented as gap in this navigation mesh; hence, pedestrians move in this navigation mesh space. Pedestrian movement and path finding in this study are both based on the built-in movement and path finding model in Pathfinder, while the pedestrian's emergency exit selection is based on the exit equilibrium method.

3.3 Scenario simulation and parameter setting

The Boeing 737-800 is an improved version of the new-generation Boeing 737NG series aircraft and suitable for medium- and short-range flights. The Boeing 737-800 has been widely used by major airlines worldwide due to its advantages of safety, reliability, simplicity, easy operation, and low maintenance cost. With high order rate and service rate, it is a typical representative. Therefore, the configuration of B737-800 is the research object in this study for building the experimental scenario. The B737-800 configuration a contains 164 seats, including 8 seats in business class, which is located in the front of the cabin, and 156 seats in economy class, which is located in the middle and rear of the cabin. The aircraft presents eight exits (a total of four entrances and exits), including one on both sides of the front and rear, with a width of 0.82 m, and two on both sides of the middle of the aircraft (a total of four emergency exits), with a width of 0.6 m. The specific layout of the aircraft is shown in Fig. 1. On the basis of the principle of maximum safety, the cabin in the evacuation scenario is set as a fully loaded environment, that is, the passenger occupancy rate is 100 %. Notably, the opening of each emergency door in the aircraft cabin requires the cooperation of one to two crew members and three passenger volunteers, the common airline crew working group is five people, and only a few scenarios will require the simultaneous opening of eight emergency exits during the evacuation process. Moreover, four exits to the left are selected before opening for the evacuation simulation analysis in the scenario design of this study given that the opening of a single side door of the cabin is more convenient for passengers to evacuate to the safe area in a unified manner in the real evacuation process. Each exit is labelled in Fig. 1.

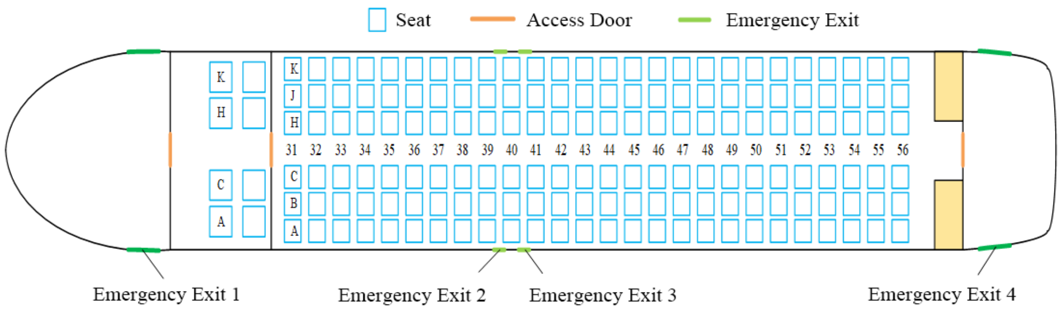


Figure 1: Cabin structure of B737-800 configuration A.

The simulation is set with the default pedestrian radius in Pathfinder after setting passengers to each seat. The passenger speed is set to 1.2 m/s for free evacuation, and this scenario is denoted S0 (control group), as shown in Fig. 2. The exit equilibrium method is added on the basis of S0 in scenario S1. The evacuation simulation is carried out by setting the exit selection of passengers in different areas. The exit selection of passengers is illustrated in Fig. 3. This study aims to ensure that the utilization rate of each exit is as consistent as possible and the convergence result does not necessarily mean that the number of pedestrians passing through each exit is exactly the same given that multiple boundary conditions exist. The convergence results of the export equilibrium simulation are 1:49, 2:39, 3:41, and 4:45. Each scenario is simulated 10 times, and the evacuation results are counted and analysed.

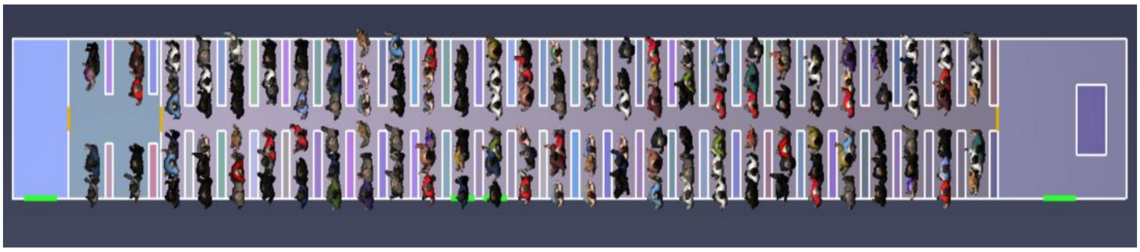


Figure 2: Scenario setting diagram.

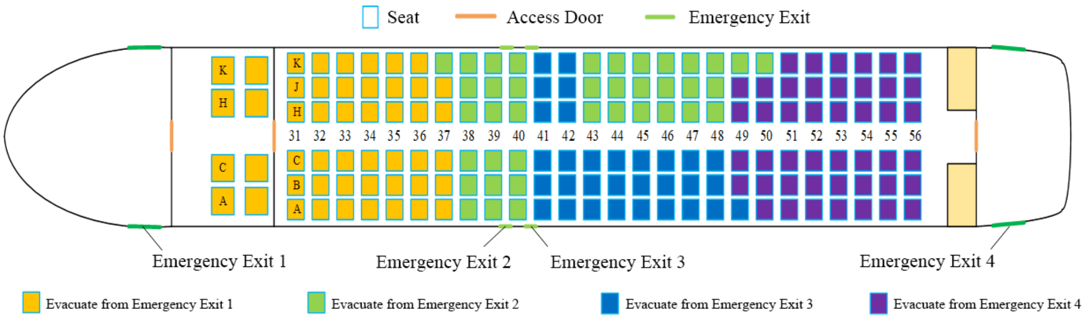


Figure 3: Exit selection of each passenger in scenario S1.

4. RESULT ANALYSIS AND DISCUSSION

4.1 Results

Exit equilibrium was applied and the Pathfinder software was used to simulate evacuation scenarios S0 and S1. The results showed that it takes an average time of 99 seconds to evacuate all passengers in scenario S0 and 86.8 seconds in scenario S1. Figs. 4 and 5 show the middle and late periods of the evacuation in scenarios S0 and S1, respectively.

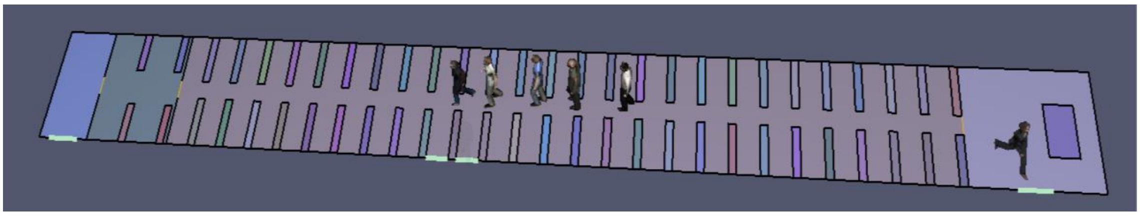
a) t = 40 s

b) t = 80 s

Figure 4: Evacuation simulation of scenario S0.

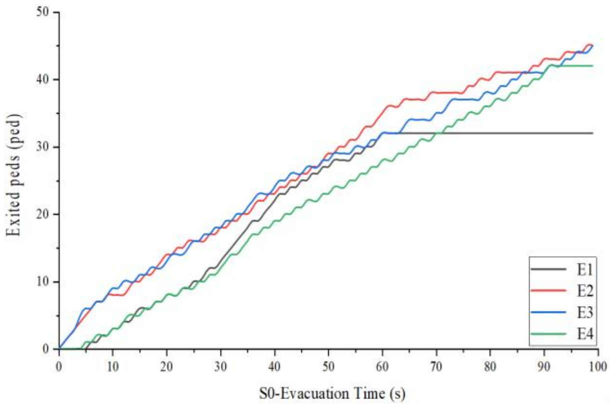
As shown in Figs. 4 and 5, the heavy counterflow crowding the aisle in scenario S0 resulted in the blockage of the evacuation exit. The excessive local density increased the difficulty for passengers to proceed. The counterflow phenomenon was alleviated to a certain extent in scenario S1 because the exit choice of each passenger was set. In addition, the crowd density and congestion area of scenario S1 are lower than those of S0 at the same time point. This finding indicated that the exit equilibrium method effectively alleviated passenger congestion. Scenario S0 can be regarded as a situation of free evacuation without instructions in the real world, while scenario S1 is a situation wherein passengers follow the crew's instructions and evacuate to the set exit. Compared with free evacuation, the evacuation with instructions from the crew saved 12.2 seconds. This finding indicated the importance of the crew's emergency instructions during the evacuation process.

a) t = 40 s

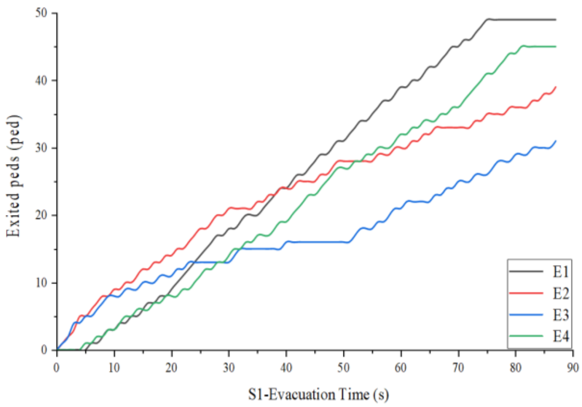


b) t = 80 s

Figure 5: Evacuation simulation of scenario S1.



a) Scenario S0



b) Scenario S1

Figure 6: Number of evacuees at each exit in scenario S0 and S1.

Fig. 6 shows the number of evacuees at each emergency exit and the change in the total number of evacuees over time in scenarios S0 and S1. The low utility ratio of exit E1 in scenario S0 without anyone using it after about 60 seconds directly caused the decrease of the overall evacuation efficiency. Many choices for passengers in front resulted in a low utility ratio of exit E1, which is located in the front of the cabin, given that passengers tend to choose the safety exit close to them during evacuation. Meanwhile, emergency exits E2 and E3 are located in the front of the cabin. The phenomenon above was evidently alleviated from the time difference between exits E1 and E4 for about 6 seconds as well as between exits E4 and E2 and E3 for about 9 seconds after using the exit equilibrium. This scenario illustrated the improvement of evacuation efficiency when the exit equilibrium method is used.

The analysis of the crowd density distribution during the evacuation in Scenario S1 demonstrated that congestion still occurs when passengers in different seating areas are simultaneously evacuated despite being arranged to evacuate at set exits (Fig. 7). The excessive local crowd density that caused congestion in the evacuation process in turn led to the unsatisfactory improvement of evacuation efficiency.

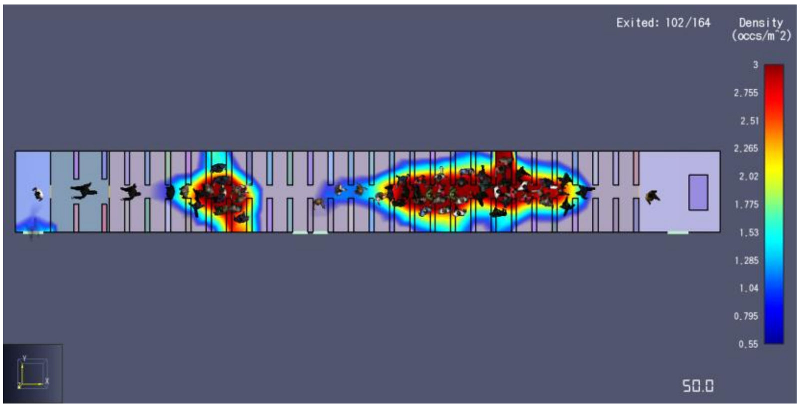


Figure 7: Local density distribution of passengers at 50 s in scenario S1.

4.2 Evacuation strategy optimization

Optimization of the evacuation sequence of passengers in scenario S1 is proposed in this study to alleviate the congestion during the evacuation process on the basis of exit equilibrium (scenario S1). The start time of evacuation of passengers from different seating areas was set via optimization to ensure that the simultaneous movement of the local crowd density caused by passengers can be reduced and avoid collision. Crew members can guide passengers from different seating areas through the evacuation sequence in the real world by communicating instructions prior to evacuation. We set the following evacuation sequences based on the exit utility equilibrium (Scenario S1) and determine the optimal strategy on the basis of the time spent evacuating all passengers according to the spatial layout of seats and safety exits of Boeing 737-800.

(1) Scenario S2: Passengers in the column near the aisle were evacuated first, followed by those in the middle and the line near the window (Fig. 8).

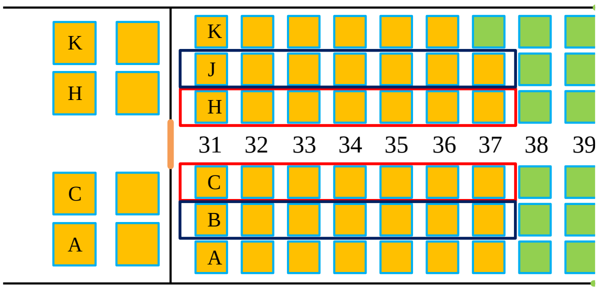


Figure 8: Diagram of passengers being evacuated first in columns near the aisle.

The evacuation process will be delayed until passengers in column H are evacuated given that passengers in columns J and K will pass those in column H on their way to emergency exits. Therefore, passengers in columns near the aisle of each seating area were prioritized in the evacuation in scenario S2 (passengers in columns C and H are outlined in red in Fig. 8), followed by passengers in columns B and J (outlined in black) and those near the window. The next batch of passengers can only begin to move when each batch of evacuees reach the front end of the column. In addition, the evacuation of passengers in business class with those prioritized can provide more space for subsequent evacuees because they can easily access the exit given that the space in business class is larger than that in economy class. The total evacuation time for scenario S2 is 79.5 seconds.

(2) Scenario S3: Passengers in the same row were evacuated in sequence (Fig. 9).

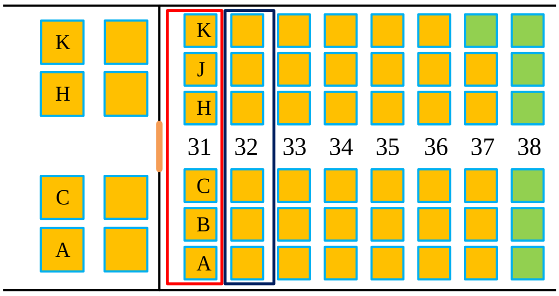


Figure 9: Diagram of the evacuation sequence of passengers in the same row.

An original row of passengers in the cabin were set as the evacuation unit in scenario S3. Passengers in rows nearest the emergency exit were evacuated first, followed by those in the next row. The next row can only begin to move when the first row of passengers have all left their seats. As shown in Fig. 9, passengers in row 31 were evacuated first, and those in row 32 and subsequent rows only began to move after proceeding to the aisle. The total evacuation time for scenario S3 is 85.9 seconds.

(3) Scenario S4: Passengers in alternate rows were evacuated in sequence (Fig. 10).

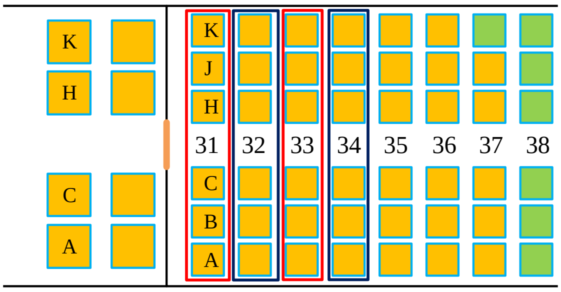


Figure 10: Diagram of passengers in alternate rows evacuating in sequence.

Passengers in rows nearest the exits and those in alternate rows in each seating area were set as priority evacuation groups in scenario S4 to alleviate the congestion in the middle and rear areas of the cabin in scenario S3. The next evacuation group can only begin to move when passengers in the latter rows succeed the former. As shown in Fig. 10, rows 31 and 33 were the priority evacuation group. The evacuation group formed by those in rows 32 and 34 and so on can only begin to move when passengers in row 33 proceeded to row 31. In this way, passengers in the latter row of the evacuation group were assured not only of enough time to proceed forward but also the reduction of waiting time in the evacuation in scenario S3, thereby improving the evacuation efficiency. The total time for evacuation is 83.8 seconds.

4.3 Analysis of optimization strategy

The optimal evacuation efficiency was achieved in scenario S2, and the total evacuation time was 19.7 seconds less than that in scenario S0, in which passengers were evacuated without instructions, and also 7.3 seconds less than that in scenario S1, in which passengers were evacuated simultaneously on the basis of exit equilibrium. The comparison of simulations showed that situations in the middle period of scenario S2 significantly improved with passengers mainly waiting in the middle of the aisle compared with those of scenario S1. Hence, this evacuation strategy effectively reduced the occurrence of congestion. Compared with that of scenario S1, congestion in the cabin alleviated to some extent in the middle period of scenario S3 and some passengers still suffered heavy congestion, especially in the middle and rear parts of the cabin. Scenario S4 was similar to scenario S3 and can be regarded as an improved version of scenario S3. The comparison of crowd density in the middle period of evacuation in scenarios

S3 and S4 demonstrated that more passengers are in the aisle and local congestion happens less frequently in scenario S4. Therefore, the average evacuation time in scenario S4 was slightly less than that in scenario S3. Notably, the average evacuation time in optimized scenarios S2, S3, and S4 was significantly less than that in scenario S0, which was set as the control scenario. Compared with scenario S1, the time was also slightly less. This finding showed that optimizing the passenger evacuation sequence on the basis of exit equilibrium is effective. Moreover, different seating areas and evacuation sequences exert strong influences on evacuation efficiency. However, evacuating passengers in columns near the aisle first, followed by those in the middle columns and near the window, is more efficient than that in the original seat sequence in the cabin regardless of the seating area of passengers. The utility ratio of each exit of the overall evacuation strategy is higher than that of the local evacuation strategy. Fig. 11 presents the number of evacuees at different emergency exits in scenario S2. The analysis of curves among the three evacuation scenarios indicated that the slope of the curve of exit E4 is the largest. This finding demonstrated that the flow rate and utility ratio of exit E4 increase in the early period of evacuation in this scenario.

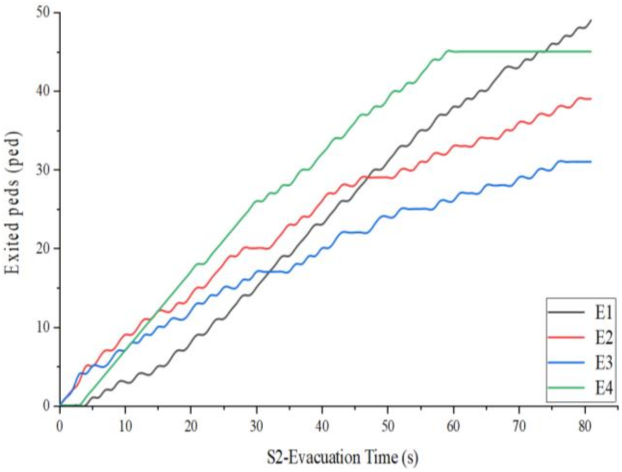


Figure 11: Number of evacuees at each exit in scenario S2.

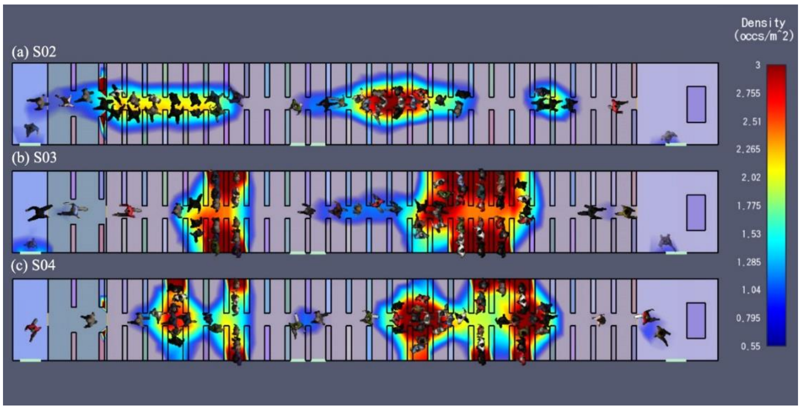


Figure 12: Local crowd density distribution of scenarios S2, S3, and S4 at 50 s.

Fig. 12 shows the comparison of the local crowd density in three optimized scenarios when $t = 50$ s. The results showed that passengers in scenario S2 are more evenly distributed mainly in the middle part of the aisle in the cabin in the three optimized scenarios, thereby avoiding collision and congestion between evacuees and passengers to be evacuated and reducing the waiting time for evacuation. However, passengers in scenario S3 were heavily congested in the front and rear parts of the cabin. Although the strategy of evacuating passengers in the same row in sequence was optimized and congestion was alleviated to some extent in scenario S4, it divided the large area of congestion in scenario S3 into several small congestion areas. Consequently, a minimal amount of time was saved in the evacuation, and the overall evacuation efficiency is unsatisfactory.

5. CONCLUSION

The A-configuration cabin of B737-800 is used as an example in this study to improve the efficiency of emergency evacuation in the aircraft cabin. The Pathfinder simulation software is used on the basis of exit flow equilibrium theory to simulate three scenarios of evacuation, including evacuation without instruction, based on exit equilibrium, and in specific sequence, and the efficiency when different evacuation strategies are applied is compared. The evacuation strategy with the minimum amount of time is proposed to analyse the main reasons for cabin congestion in evacuation. The following conclusions can be drawn from this study:

(1) The special structure of aircraft cabin is the key factor affecting passenger evacuation efficiency. The evacuation time is 99 seconds in the case of emergency without effective instruction from crew members. However, the average evacuation time can be saved by 12.2 seconds when evacuation exits for passengers are arranged in a reasonable and balanced manner, thereby indicating that instructions of crew members play a crucial role in the evacuation efficiency.

(2) The occurrence of counterflow and local crowd density in the cabin can be reduced to a certain extent according to exit equilibrium and a reasonable evacuation sequence of passengers in different seating areas to improve evacuation efficiency.

(3) On the basis of exit equilibrium, the optimal evacuation efficiency can be achieved by evacuating passengers first in columns near the aisle, followed by passengers in the middle and near the window. This evacuation strategy can effectively alleviate congestion in the cabin aisle, reduce the waiting time for evacuation, and facilitate the movement of passengers to the cabin aisle as soon as possible. Hence, the minimum evacuation time is achieved.

In conclusion, the Pathfinder simulation software can be used to analyse the efficiency of crowd evacuation in a confined space, such as an airplane cabin, and identify the bottleneck in the evacuation process effectively. Combined with traffic flow equilibrium theory, a safe and efficient evacuation strategy can be formulated on the basis of the distribution of emergency exits in different spatial structures to provide time safety for emergency management and rescue work of air transport. The concept of noncompletely rational person in emergency evacuation can be introduced into future evacuation investigations to improve the authenticity and accuracy of the simulation.

ACKNOWLEDGEMENTS

This study was supported by the Science and technology planning project of Henan Province in China (212102310384, 222102320384, 222102320454).

REFERENCES

[1] Moon, K.; Yakovlev, A. A. (2020). A comparative statistical analysis of global trends in civil helicopter accidents in the U.S. the EU, and the CIS, *IOP Conference Series: Materials Science and Engineering*, Vol. 868, No. 1, Paper 012020, 11 pages, doi:10.1088/1757-899X/868/1/012020

[2] Gobbin, A.; Khosravi, R.; Bardenhagen, A. (2021). Emergency evacuation simulation of commercial aircraft, *SN Applied Sciences*, Vol. 3, No. 4, Paper 446, 13 pages, doi:10.1007/s42452-021-04295-z

[3] Jasztal, M. (2020). Testing the process of evacuation from the passenger aircraft with the use of computer simulation, *Safety & Fire Technology*, Vol. 56, No. 2, 22-39, doi:10.12845/sft.56.2.2020.2

[4] Zhou, Z.; Chen, A.; Bekhor, S. (2012). C-logit stochastic user equilibrium model: formulations and solution algorithm, *Transportmetrica*, Vol. 8, No. 1, 17-41, doi:10.1080/18128600903489629
[5] Hedo, J. M.; Martinez-Val, R. (2011). Assessment of narrow-body transport airplane evacuation by numerical simulation, *Journal of Aircraft*, Vol. 48, No. 5, 1785-1794, doi:10.2514/1.C031397
[6] Zambrano, J. A.; Huertas, J. A.; Segura-Duran, E.; Medaglia, A. L. (2020). Time estimation and hotspot detection in the evacuation of a complex of buildings: a mesoscopic approach and case study, *IEEE Transactions on Engineering Management*, Vol. 67, No. 3, 641-658, doi:10.1109/TEM.2019.2960354
[7] Wang, F. (2021). Multi-scenario simulation of subway emergency evacuation based on multi-agent, *International Journal of Simulation Modelling*, Vol. 20, No. 2, 387-397, doi:10.2507/IJSIMM20-2-CO8
[8] Isobe, M.; Helbing, D.; Nagatani, T. (2004). Experiment, theory, and simulation of the evacuation of a room without visibility, *Physical Review E*, Vol. 69, No. 6, Paper 066132, 10 pages, doi:10.1103/PhysRevE.69.066132
[9] Okada, N.; Hasemi, Y.; Moriyama, S. (2012). Feasibility of upward evacuation by escalator – an experimental study, *Fire and Materials*, Vol. 36, No. 5-6, 429-440, doi:10.1002/fam.1118
[10] Muhammed, D. A.; Rashid, T. A.; Alsadoon, A.; Bacanin, N.; Fattah, P.; Mohammadi, M.; Banerjee, I. (2020). An improved simulation model for pedestrian crowd evacuation, *Mathematics*, Vol. 8, No. 12, Paper 2171, 14 pages, doi:10.3390/math8122171
[11] Kim, H.; Han, S. (2018). Crowd evacuation simulation using active route choice model based on human characteristics, *Simulation Modelling Practice and Theory*, Vol. 87, 369-378, doi:10.1016/j.simpat.2018.07.014
[12] Fang, Z.-M.; Lv, W.; Liu, X.-D.; Song, W.-G. (2014). Study of Boeing 777 evacuation using a finer-grid civil aircraft evacuation model, *Transportation Research Procedia*, Vol. 2, 246-254, doi:10.1016/j.trpro.2014.09.044
[13] Wang, X.; Liu, Z.; Zhao, Z.; Wang, J.; Loughney, S.; Wang, H. (2020). Passengers' likely behaviour based on demographic difference during an emergency evacuation in a Ro-Ro passenger ship, *Safety Science*, Vol. 129, Paper 104803, 17 pages, doi:10.1016/j.ssci.2020.104803
[14] Burigat, S.; Chittaro, L. (2016). Passive and active navigation of virtual environments vs. traditional printed evacuation maps: a comparative evaluation in the aviation domain, *International Journal of Human-Computer Studies*, Vol. 87, 92-105, doi:10.1016/j.ijhcs.2015.11.004
[15] Haghani, M. (2020). Empirical methods in pedestrian, crowd and evacuation dynamics: Part I. Experimental methods and emerging topics, *Safety Science*, Vol. 129, Paper 104743, 42 pages, doi:10.1016/j.ssci.2020.104743
[16] Liu, Y.; Wang, W.; Huang, H.-Z.; Li, Y.; Yang, Y. (2014). A new simulation model for assessing aircraft emergency evacuation considering passenger physical characteristics, *Reliability Engineering & System Safety*, Vol. 121, 187-197, doi:10.1016/j.ress.2013.09.001
[17] Chang, Y.-H.; Liao, M.-Y. (2008). Air passenger perceptions on exit row seating and flight safety education, *Safety Science*, Vol. 46, No. 10, 1459-1468, doi:10.1016/j.ssci.2007.11.006
[18] Giuseppi, A.; Pietrabissa, A. (2021). Wardrop equilibrium in discrete-time selfish routing with time-varying bounded delays, *IEEE Transactions on Automatic Control*, Vol. 66, No. 2, 526-537, doi:10.1109/TAC.2020.2981906
[19] Babicheva, T. S. (2016). About possible methods of generalization the Beckmann's model, taking into account traffic light modes on the transport graph nodes, *Procedia Computer Science*, Vol. 91, 101-108, doi:10.1016/j.procs.2016.07.046
[20] Jiang, Y. L.; Gai, W. S.; Li, Q. (2021). Research on rapid prediction model of indoor personnel evacuation time, *Journal of Safety Science and Technology*, Vol. 17, No. 4, 30-34, doi:10.11731/j.issn.1673-193x.2021.04.005
[21] Shier, D. R. (1981). A computational study of Floyd's algorithm, *Computers & Operations Research*, Vol. 8, No. 4, 275-293, doi:10.1016/0305-0548(81)90015-0