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Research Article

Optimization of an Airport Departure Hall Evacuation Plan Based on a Time-Varying Network Algorithm

Yueya Shi,[1] **Wei Sun**,[1] **Yuankai Wu**,[2] **and Guojun Zeng**[3,4]

[1]*School of Airport, Civil Aviation Flight University of China, Guanghan 618307, China*
[2]*College of Computer Science, Sichuan University, Chengdu 610065, China*
[3]*Med-X Center for Informatics, Sichuan University, Chengdu 610065, China*
[4]*West China Hospital, Sichuan University, Chengdu 610041, China*

Correspondence should be addressed to Guojun Zeng; zengguojun@wchscu.cn

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As a highly dense area for passengers, the airport departure hall is particularly characterized by the easy gathering of passengers, irregularity, and difficulty in command, which has become a high incidence of emergencies. For the evacuation problem in case of emergencies, the vast majority of passengers randomly choose the shortest path from the exit to escape, which will lead to congestion at some nodes and prolonging of the evacuation time. Therefore, this study proposes a better evacuation method considering the dynamic change in the spatiotemporal congestion of passengers. First, this paper constructs an evacuation network diagram for the departure hall of the Shenzhen Bao'an International Airport terminal building, simplifies the evacuation process into point-to-point evacuation, and proposes a time-varying network algorithm to optimize the emergency evacuation of the airport. Second, on the premise of obtaining the number and dynamic distribution of passengers in each area in real time, a linear programming model with the shortest evacuation time as the optimization objective is established, and the current optimal evacuation path of passengers is dynamically calculated. Finally, the two evacuation methods, random evacuation and evacuation, based on a time-varying network algorithm are simulated and analyzed by AnyLogic software. The results show that the evacuation scheme based on the time-varying network algorithm can effectively relieve the passenger congestion of some evacuation paths and safety exits. The evacuation time is reduced by 74 s, the evacuation efficiency is improved by 14%, passenger congestion at some evacuation routes and safety exits can be effectively relieved, and the global optimization of the emergency evacuation of passengers is achieved.

1. Introduction

The Civil Aviation Administration of China was deployed to implement "paperless" convenient travel services across the industry. Civil aviation is becoming more and more intelligent, travel is becoming more and more convenient, and travel by air has become the choice of more and more people. As a result, the terminal building has become a dense area for passengers in the airport, and in the event of an emergency, the traditional evacuation method leaves some passengers unable to find an effective escape route in time and makes the terminal area prone to regional congestion. Therefore, it is important to study the optimization of the emergency evacuation plan for passengers in terminal buildings. Previously, some experts have performed related research. Antonova et al. [1] employed AnyLogic software to analyze inbound passenger flow to check congestion points. Yang et al. [2] sought to meet the transportation demand for taxis and alleviate the problem of mismatch between the supply and demand of taxis. Guo et al. [3] used the exit flow equilibrium method based on crowd evacuation dynamics theory to clarify the reasons that hinder the evacuation of aircraft cabin passengers. Han et al. [4] proposed an extended route selection model based on the set of available evacuation routes to simulate the choice of pedestrians in selecting the appropriate route during evacuation in emergency situations. Khamis et al. [5] proposed an artificial bee colony optimization method based on a stochastic approach, which requires fewer control parameters to be adjusted in finding the optimal exit. Zhao et al. [6] improved the efficiency of pedestrian evacuation through different obstacle types. Jin et al. [7] compared different evacuation strategies in subway under node failure situation. To further investigate the influence of adjacent exit evacuation behavior and familiarity on exit selection, Kinateder et al. [8] conducted the first experimental test of the exit familiarity assumption and investigated how it interacts with social influences to determine exit selection during evacuation. Kallianiotis et al. [9] studied the effect of passenger evacuation speed and evacuation route selection on evacuation time. Fahad et al. [10] studied the factors influencing the severity of damage and predicted the number of future collisions. Li [11] analyzed the effect of indoor space layout on evacuation efficiency. Jiaojiao and Jin [12] established an evaluation system on the analysis of passenger evacuation bottleneck factors and proposed a risk evaluation method. Jiang et al. [13] simulated the evacuation process through simulation software and analyzed the congestion characteristics of the platform stairs during peak hours. Wang et al. [14] discussed the influence of risk factors on the frequency of urban traffic accidents while considering the temporal and spatial correlation and heterogeneity of traffic accidents. Li et al. [15] took the old dormitory building of a large university as an example and used the Pathfinder software platform to perform multiple evacuation simulations with parameter settings for the building and occupants. Chen et al. [16] examined the influence of socioeconomic factors, travel day characteristics, and behavioral factors on evacuation and destination selection decisions.

Recently, the dynamic evacuation problem has become a hot research topic. Zhang et al. [17] proposed to solve the path optimization problem based on a priori evacuation network with the breadth-first search strategy and dynamically update the evacuation path based on real-time information. Hu and Cai [18] proposed a method to improve the evacuation efficiency of people on board cruise ships by controlling the density of passengers. Cao et al. [19] developed a microscopic simulation model to describe the fuzzy behavior of pedestrians under view-limited conditions and defined seven fuzzy sets for the evacuation process. Wang et al. [20] proposed a mixed integer nonlinear multiobjective programming model and used a combination of simulated annealing (SA) algorithm and particle swarm optimization (PSO) algorithm to solve the complex model. Liu et al. [21] presented a real-time evacuation route approach based on emotion and geodesic under the influence of individual emotion and multihazard circumstances. Yu et al. [22] developed dynamically updatable data structures and a matrix-based greedy search algorithm to support dynamic evacuation path search for multiple evacuees. Facing the dynamic situation, Zhao et al. [23] used dynamic planning to search for the optimal paths and informed everyone how to move toward the exit. Neural networks are good at learning the hidden knowledge from sample date. Peng et al. [24] used neural networks to decide which paths are available for people to evacuate dynamically.

Effective emergency evacuation routes are essential for the safety of people in an accident, and the basic requirement is that travelers get the best route in a short time to adapt to dynamic changes [17]. Based on dynamic evacuation, can the traditional evacuation scheme be further optimized if the real-time change of spatiotemporal crowding is considered. Therefore, this study intends to propose a dynamic evacuation path optimization method to change the optimal evacuation path of passengers in real time by considering the spatiotemporal crowding of regional passengers.

2. Constructed Evacuation Network Diagram

2.1. Airport Departure Hall Plan. In this paper, we focus on the efficiency of passenger evacuation at the departure hall of Shenzhen Bao'an International Airport as a simulation site, and the plan of the departure hall is shown in Figure 1. Passengers first enter the departure hall from the gate lobby and then check in at different check-in areas (such as self-service check-in, manual check-in, and VIP lounge check-in); if they have large luggage, they need to go to the check-in counters on both sides of the departure hall for check-in and finally arrive at the security check waiting area to queue for the security check through these security check channels.

2.2. Evacuation Network Diagram. The evacuation rules are set as follows: from the moment of starting evacuation, all business handling areas (check-in area and security check waiting area), nonbusiness handling areas (stores, toilets, rest areas, etc.), and passengers who have not completed a security check stop active processes, and then passengers immediately seek to reach the safety area through gates 1 to 7, and the evacuation process ends when the number of passengers in the departure hall is 0.

In this paper, the evacuation process is simplified to point-to-point evacuation, so the departure hall floor plan is abstracted into source nodes, root nodes, and edges to form an evacuation network diagram, as shown in Figure 2. In the evacuation process of passengers in the departure hall, all of the areas where passengers are to be evacuated (such as the security check waiting area, security check waiting area entrance area, check-in area, and other business processing areas and nonbusiness processing areas such as stores, toilets and rest areas) can be attributed to the source node in the area by using the principle of proximity and travel to the root node (safety exit) through the optional evacuation path (edge) to complete the overall process. The evacuation network has 38 source nodes in the security check waiting area, which is set as the A area, with each source node in turn set as $A1$–$A38$ from top to bottom; the security check waiting area entrance area has four source nodes, which is set as the B area, with each source node in turn set as $B1$–$B4$ from top to bottom; the check-in area has 19 source nodes, which is set as the C area, with each source node in turn set as $C1$–$C19$ from top to bottom. There are seven root nodes in the security exit area, and this area is designated as the D area, with each root node represented from top to bottom by $D1$–$D7$. In addition, there are various obstacles in the evacuation

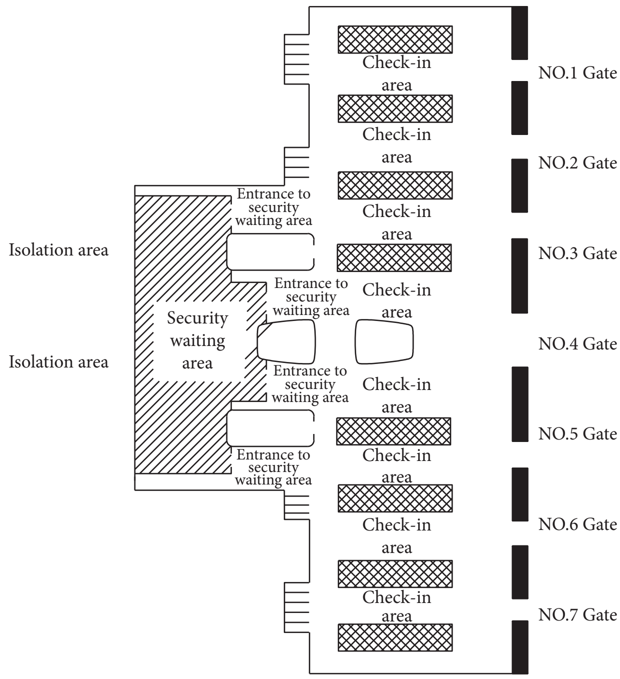

Figure 1: Floor plan of the departure hall.

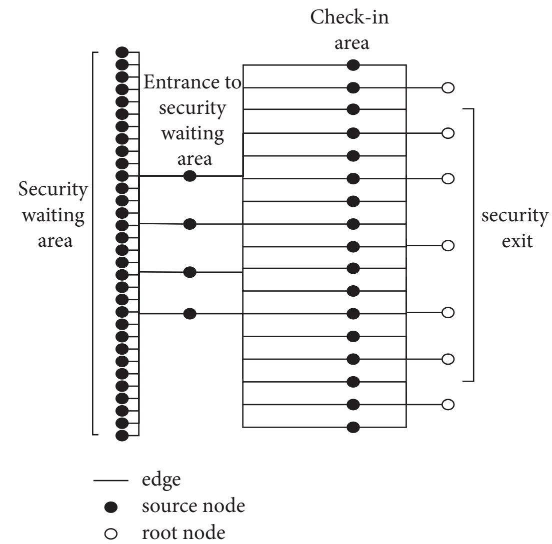

Figure 2: Evacuation network model.

process of the terminal departure hall because all passengers to be evacuated are evacuated in the same direction, and the obstacles do not block the evacuation nodes, so this study does not consider the obstacles and only calculates the physical distance between nodes.

3. Evacuation Model Based on the Time-Varying Network Algorithm

The paper establishes a linear programming model based on time-varying network algorithm evacuation rules to derive the optimal evacuation path set under the time-varying network algorithm evacuation rules to minimize the evacuation time of all passengers and achieve the global optimization of emergency evacuation of passengers by considering the spatial and temporal congestion of regional passengers.

3.1. Randomized Evacuation Rule Based on the Shortest Circuit Algorithm. In the unguided conduct of random emergency evacuation, to reach the safe area as soon as possible, each traveler tends to choose the shortest evacuation path. Therefore, the principle of shortest circuit-based evacuation is that the traveler follows the physically shortest edge from the source node to the root node. The paper assumes that all traveler behaviors are based on the shortest path principle when using the random evacuation rule.

Therefore, if passengers are not evenly distributed at the beginning of the evacuation, the process may result in the majority of passengers concentrating on the few evacuation paths with the shortest distance to the safety point, which will inevitably result in congestion.

3.2. Evacuation Rules Based on the Time-Varying Network Algorithm. The shortest evacuation distance during passenger evacuation does not mean the shortest evacuation time, so the concept of spatiotemporal crowding is introduced. Spatiotemporal congestion is a description of the degree of congestion of moving objects in time and space [25]. According to the actual spatial distribution, each node in the terminal building corresponds to a slice region, and the object of the spatiotemporal crowding degree study is the region, so this paper precisely discusses the spatiotemporal crowding degree of the slice region corresponding to the node (hereafter referred to as the spatiotemporal crowding degree of the node).

In the evacuation process, travelers will pass through their respective evacuation paths and reach the safety area at different moments. The spatiotemporal trajectory is sliced at the jth time interval at node i. The total number of people at the node in the time interval is counted as the area of the node corresponding to the sliced area, and the final value of the spatiotemporal congestion of the travelers in the area at the jth time slice in the ith node is obtained:

$$F\left(i, \Delta t_j\right) = \frac{N_i}{P_i} \cdot \Delta t_j. \quad (1)$$

When studying passenger evacuation paths based on a time-varying network algorithm, it is necessary to set the upper limit of a reasonable value of spatiotemporal congestion in advance, unified as 2 in this paper; that is, when $0 < F(i, \Delta t_j) < 2$, the spatiotemporal congestion of the sliced area where the node is located is within a reasonable range. In addition, to simplify the model, it is stipulated that all passengers in any slice area automatically belong to the corresponding node; that is, the corresponding node in the slice area is regarded as the departure point for evacuating passengers in that area.

Before each real-time optimization of the passenger emergency evacuation path, it is necessary to determine whether the time of Δt_j congestion within the time slice on the next target node i is within a reasonable range, that is, whether the passenger selection of this evacuation path can guarantee the evacuation speed. Based on Dijkstra's algorithm, the time-varying network algorithm is established by dynamically calculating the spatial and temporal congestion of regional travelers.

The optimal evacuation path is recalculated under the existing $F(i, \Delta t_j)$ for each passenger to be assigned an evacuation path. The specific rules are as follows [26]:

Step 1: Determine the starting evacuation location of passengers as the starting point of the time-varying network algorithm search.

Step 2: Due to the congestion in the evacuation process, the calculated lengths of all evacuation paths are no longer static and individually calculated, but the spatiotemporal congestion of the next destination node is considered.

Step 3: The next destination node with the shortest evacuation time is selected by the linear programming model calculation of the time-varying network algorithm.

Step 4: Determine whether all subsequent selectable destination nodes have been computed, and if so, generate a traveler evacuation path; otherwise, continue the computation.

Step 5: The path with the shortest evacuation time is selected as the searched area, and the current optimal evacuation path and the moment of passing through it are updated.

Step 6: Each time the calculation is completed, a new evacuation path P_i is generated. P_i is the optimal evacuation path for travelers at that node, the path is assigned to each traveler m, and the spatiotemporal congestion of regional travelers in all current evacuation paths is updated.

Step 7: Returning to Step 1, the optimal evacuation path of the next passenger m to be evacuated is calculated cyclically, and the evacuation path of passenger m is recalculated each time based on the spatiotemporal congestion on the evacuation path of $m-1$ passengers according to equation (1) until all passengers are evacuated. The flow chart of the time-varying network algorithm is shown in Figure 3 [27].

In summary, the time-varying network algorithm-based evacuation rule is used to assign optimal evacuation paths to travelers by calculating the spatiotemporal congestion of the time slices of the nodes and setting the real-time capacity limits of the area. The core of the algorithm lies in building a mathematical model to assist in choosing the dominant path, which will be discussed in the next subsection [28].

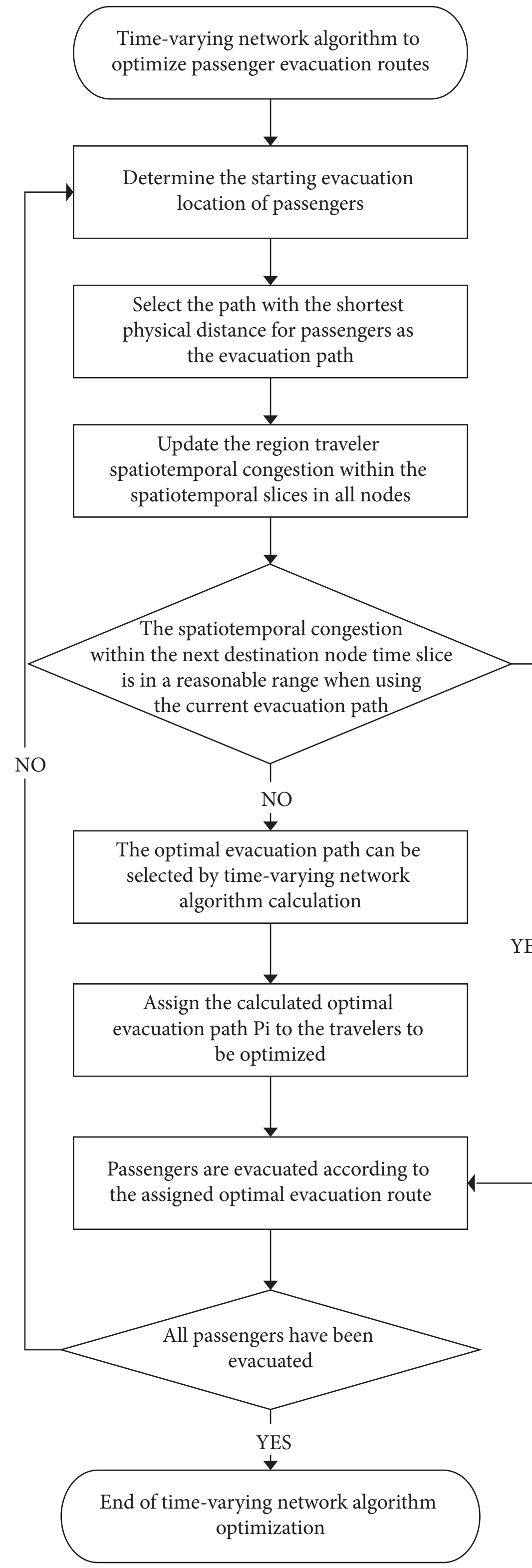

Figure 3: Time-varying network algorithm.

3.3. Linear Programming mWodel Based on the Time-Varying Network Algorithm. Based on the analysis of the spatiotemporal congestion of passengers, combined with the shortest circuit theory, the linear programming model of the time-varying network algorithm is established to determine the target exit and dominant path of different groups by calculating the minimum evacuation time. Finally, the evacuation path assigned to each group of passengers is the relative dominant path, and all evacuation paths achieve a

Table 1: Passenger evacuation status.

Evacuation status	Regional spatial-temporal congestion	Gender	Evacuation speed (m/s)
No obstacles	1	Male	1.6
		Female	1.5
Faster	1-2	Male	1
		Female	0.8
Sight obstruction	2-3	Male	0.5
		Female	0.4
Slow	4.7	Male	0.3
		Female	0.3
Unable to evacuate	5.38	Male	0
		Female	0

uniform number of people with similar time consumption and spatiotemporal congestion within the set range.

The overall evacuation path of this algorithm is divided into three segments, and each segment finds the corresponding optimal evacuation path by calculating the shortest evacuation time of passengers.

(1) Evacuation from area A to area B:

$$T_{n1} = S_{n1} + S_{n2}. \tag{2}$$

Here, T_{n1} indicates the shortest evacuation time of passengers in the security waiting area (zone A) from the source node where they are located to a source node at the entrance of the security waiting area (zone B).

$$\begin{cases} S_{n1} = B\left(i, \Delta t_j\right) \cdot A \cdot \min \sum\limits_{b=1}^{4} \dfrac{A_i B_b}{v} \cdot \Delta t_j, \\ S_{n2} = \left(1 - B\left(i, \Delta t_j\right)\right) \cdot A \cdot \min \sum\limits_{\substack{e=1 \\ e \neq b}}^{4} \dfrac{A_i B_e}{v} \cdot \Delta t_j, \\ A = 0 \text{ or } 1; B\left(i, \Delta t_j\right) = 0 \text{ or } 1, \end{cases} \tag{3}$$

where A is 1 when passenger n is at the source node of the security waiting area, and 0, otherwise. When the temporal congestion in any of the sliced areas corresponding to the four nodes at the entrance to the security waiting area (area B) is within a reasonable range, at which $B(i, \Delta t_j) = 1$, S_{n1} is the shortest evacuation time from area A to area B within the time slice; if the spatiotemporal congestion in any area is not within a reasonable range, then $B(i, \Delta t_j) = 0$; that is, the shortest evacuation time from area A to area B within the time slice is denoted by S_{n2}. At this time, the source node b corresponding to the minimum value of spatiotemporal congestion $F(i, \Delta t)$ is taken as the next target point in the optimized path, and $e = b$. A_iB_b, A_iB_e denotes the distance from a node in area A to a node in area B. v is the evacuation speed within the time slice of the traveler, and the evacuation speed is related to the gender of the traveler and the spatiotemporal congestion of the area, as shown in Table 1.

(2) Evacuation from area B to area C:

$$T_{n2} = S_{n3} + S_{n4}. \tag{4}$$

Here, T_{n2} indicates the shortest evacuation time from the source node where the passenger is located to a source node in the check-in area (Area C) at the entrance to the security waiting area (Area B).

$$\begin{cases} S_{n3} = B\left(i, \Delta t_j\right) \cdot B \cdot \min \sum\limits_{c=1}^{19} \dfrac{B_i C_c}{v} \cdot \Delta t_j, \\ S_{n4} = \left(1 - B\left(i, \Delta t_j\right)\right) \cdot B \cdot \min \sum\limits_{\substack{f=1 \\ f \neq c}}^{19} \dfrac{B_i C_f}{v} \cdot \Delta t_j, \\ B = 0 \text{or} 1; B\left(i, \Delta t_j\right) = 0 \text{ or } 1, \end{cases} \tag{5}$$

where B is 1 when passenger n is in the security check waiting area entrance source node; otherwise, it is 0. When the slicing area corresponding to 19 nodes in the check-in area (C area) which has any one area where the temporal congestion is within a reasonable range, then $B(i, \Delta t_j) = 1$, that is, S_{n3} is the shortest evacuation time from area B to area C within the time slice; if the spatiotemporal congestion in any region is not in a reasonable range, $B(i, \Delta t_j) = 0$, and the shortest evacuation time from region B to region C within the time slice is denoted by S_{n4}. At this point, the source node c corresponding to the minimum value of spatiotemporal congestion $F(i, \Delta t)$ is taken as the next target point in the optimization path and $f = c$. B_iC_i, B_iC_f denotes the distance from a node in region B to a node in region C.

(3) Evacuation from area C to area D:

$$T_{n3} = S_{n5} + S_{n6}. \tag{6}$$

Here, T_{n3} indicates the minimum evacuation time of passengers in the check-in area (Area C) from the source node where they are located to a source node at the security exit (Area D).

$$
\begin{cases}
S_{n5} = B\left(i, \Delta t_j\right) \cdot C \cdot \min \sum_{d=1}^{7} \frac{C_i D_d}{v} \cdot \Delta t_j, \\
S_{n6} = \left(1 - B\left(i, \Delta t_j\right)\right) \cdot C \cdot \min \sum_{\substack{g=1 \\ g \neq d}}^{7} \frac{C_i D_g}{v} \cdot \Delta t_j, \\
C = 0 \text{ or } 1; B\left(i, \Delta t_j\right) = 0 \text{ or } 1,
\end{cases} \quad (7)
$$

where C is 1 when traveler n is in the source node of the value plane area; otherwise, it is 0. When the temporal congestion of any one of the sliced areas corresponding to the seven nodes of the security exit (D area) is within a reasonable range, then $B(i, \Delta t_j) = 1$; that is, S_{n5} is the shortest evacuation time from the C area to the D area within the time slice; if the temporal congestion of any one area is not within a reasonable range, then $B(i, \Delta t_j) = 0$; that is, the shortest evacuation time from the C area to the D area within the time slice is expressed by S_{n6}. At this point, the source node d corresponding to the minimum value of spatiotemporal congestion $F(i, \Delta t)$ is taken as the next target point in the optimization path, and $g = d.C_i D_d, C_i D_g$ denotes the distance from a node in zone C to a node in zone D.

(4) Overall evacuation time T:

$$
T = \max \sum_{n=1}^{z} \left(T_{n1} + T_{n2} + T_{n3}\right), \quad (8)
$$

where z is the total number of people in the terminal at the time of evacuation, and T is the overall evacuation time; that is, the time when the last passenger in the terminal evacuated to the safety exit also marks the end of the overall evacuation process.

4. Simulation Process and Result Analysis

4.1. Data Selection

(1) Peak hour refers to the time period in which the airport terminal has the highest passenger flow. The peak hour at Shenzhen Bao'an International Airport is from 9:00 to 9:59 a.m. Based on the passenger occupancy rate, and calculated according to the average passenger occupancy rate of 80% for regular domestic flights in the civil aviation industry, the number of passengers during the airport peak hour is approximately 3,300:

$$
A = \sum_{i=1}^{n} b_i \cdot O. \quad (9)
$$

Here, A is the number of passengers in the selected time period, n is the number of departures in the peak hour at the airport, b_i is the maximum capacity of the flight, and O is the average passenger seat rate of the flight in the civil aviation industry.

Table 2: Passenger flow time.

Business handling time	Passenger time interval (s/person)
Artificial check-in	60–90
Self-service check-in	60–120
Large baggage check-in counter	100–180
VIP check-in	60–120
Security check	90–150

Table 3: Characteristics of passengers to be evacuated.

Category	Adult male	Adult female
Shoulder width (cm)	40	37
Proportion	0.5	0.5

(2) Passenger process time is as shown in Table 2, and the data were acquired from 100 randomly selected passengers (including different attributes, such as different ages, genders, amounts of luggage carried, and different levels of familiarity with the ticketing process) on-site every day in January 2022. The average time interval of each process for each person was obtained after 30 days of monitoring, and the passenger time was represented by a normal distribution.

(3) Proportion of passengers using check-in islands: Based on the statistics of the number of flights of each airline in the airport from 9:00–9:59 each day in January 2022, the proportion of passengers going to different check-in islands for check-in is derived.

(4) The characteristics of the passengers to be evacuated are shown in Table 3

(5) Passenger evacuation speed: Table 1 shows the values of evacuation speed for passengers of different genders under different evacuation states and with temporal and spatial crowding.

4.2. Simulation Model Construction. First, the CAD drawing is imported into the main view of AnyLogic software; second, the internal facilities (such as terminal perimeter, security check area, and check-in area) are created by the corresponding modules in the software. The model in the software is presented as a flowchart of passenger behavior, which is realized by modules such as PedSource, PedGoTo, PedService, PedSink, and PedSelectOutput. The model constructed in this paper includes two parts: departure process and passenger emergency evacuation.

In the event of an emergency in the departure lobby, the "Evacuate" button initiates the passenger evacuation mode, at which point the PedSource module stops generating passengers, indicating that no more passengers are entering the terminal, and the evacuation process is realized through the lower ports of each module. When emergency evacuation begins, all passengers in the module enter the connected PedGoTo module through the lower port. The shortest circuit algorithm and the time-varying network algorithm are written in JAVA as function modules and incorporated into the PedGoTo module of the evacuation process, which means that when the passengers enter the PedGoTo module, the function is run to calculate the result: the optimal evacuation path for the passengers. Another event module is set to define the evacuation speed of passengers, and the corresponding conditional statements are written according to Table 1 to show the evacuation speeds of passengers under different temporal and spatial congestion conditions.

4.3. Simulation Analysis of Evacuation Based on the Principle of the Shortest Circuit. The process of terminal passenger evacuation simulation is as follows: according to the business processes of departing passengers, departing passengers move inside the terminal building, and when the number of passengers entering the terminal building inside the departure hall reaches 3,300, after several simulations, the average number of passengers not passing the security check inside the terminal building is assumed to be 1,300.

With these 1,300 people evacuated, the simulation was initiated according to the principle of the shortest circuit until the number of passengers in the departure hall was 0. The curve of the number of evacuees at each exit as a function of time after 30 simulations is shown in Figure 4.

From Figure 4, it can be determined that all passengers evacuate to the safe area in 496 s. *B* and *D* are bottleneck areas for evacuation mainly because of the uneven distribution of equipment. In *D*, doors 3 and 5 maintain a high number of passengers evacuated from the beginning of evacuation to the end of evacuation, the curve corresponding to door 4 has an inflection point at 150 s, and the slope change increases when passengers in the security check waiting area start to use door 4 for evacuation. The numbers of evacuees at exits 1, 2, 6, and 7 after 150 s are nearly constant, indicating that passengers do not use these four exits. Among all exits, the numbers of passengers using doors 3, 4, and 5 to complete the evacuation are the largest, and the numbers of evacuees using doors 1 and 2 are the smallest.

Comprehensive analysis of the first simulation results shows that to reach the safe area as soon as possible, most travelers follow the principle of the shortest circuit, so some shorter surface routes will be chosen by too many people, leading to increased spatiotemporal congestion and slower escape speed. In addition, the herd mentality also aggravates the congestion of these paths.

4.4. Simulation Analysis of Evacuation Based on a Time-Varying Network Algorithm. The above discussion shows that the optimal evacuation path changes in real time, and the shortest path is not the optimal path for the dynamic evacuation process, while some evacuation paths are not advantageous in terms of length but become the new optimal path because of their rapid escape speed. The evacuation method based on the time-varying network algorithm reflects these ideas.

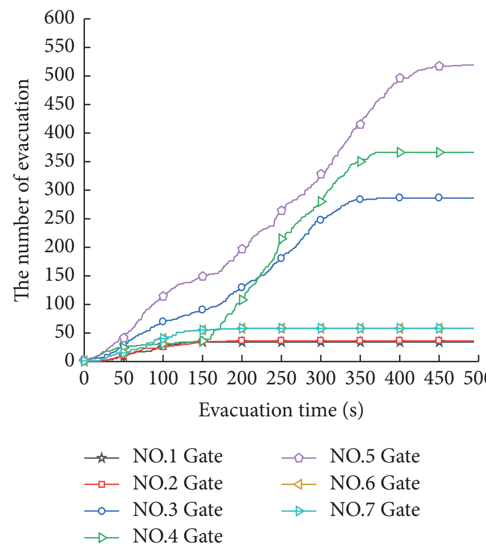

Figure 4: The number of evacuees at each exit changes with time.

The time slice Δt_j of the new algorithm is set to 1 second in the simulation; that is, it is calculated once every 1 second in the background. To prevent travelers from repeatedly switching between two different evacuation paths, the algorithm sets the self-triggering time interval to 5 seconds: when the spatiotemporal congestion of an evacuation node is not within a reasonable range, those travelers of this evacuation node who need to change their routes receive the updated path every 5 seconds (for the convenience of calculation, the transition time is uniformly set to 0 seconds; that is, after updating the path, travelers can immediately implement evacuation along the new path). The interval between two adjacent updates of evacuation paths by passengers also must not exceed 5 seconds [29]. In this way, in practical application, the application software refreshes the evacuation path every 5 seconds, and the change time of the path is greater than or equal to 5 seconds, which reduces the inconvenience to passengers caused by the rapid change of the evacuation path.

After 30 simulations were averaged, the curve of the number of evacuees at each exit as a function of time was obtained, as shown in Figure 5. Compared with Figure 4, there is no significant inflection point in any curve after optimization, and the temporal crowding of passengers at each exit is within the permissible range. Most of the exits were reasonably used in the evacuation process. The traffic of the original congested Gate 5 was diverted to Gates 6 and 7, and Gates 2 and 3 were chosen by some passengers as the second-best path, which also played a diverting role. Passengers of Gate 5 were the first to evacuate to the safety area, approximately 5 s after the start of evacuation, while those of Gate 1 started to evacuate to the safety area only at 30 s. This is because most passengers were closest to Gate 5 and farthest from Gate 1 during the evacuation process.

Figure 6 shows the comparison of the number of evacuees at each exit before and after optimization. Analysis shows that after optimization, the number of evacuees at Gates 4 and 5 is significantly reduced compared with that

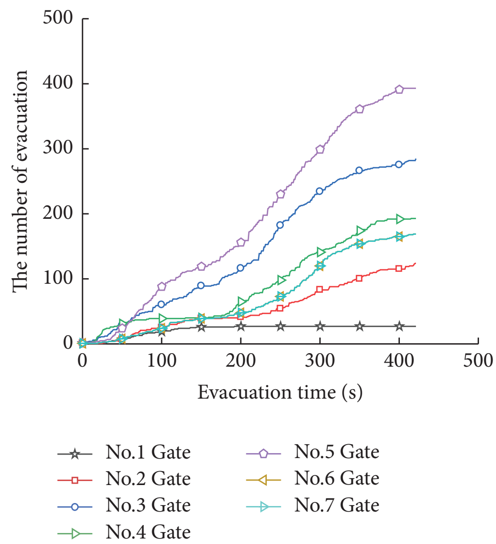

Figure 5: The number of evacuees at each exit changes with time after evacuation.

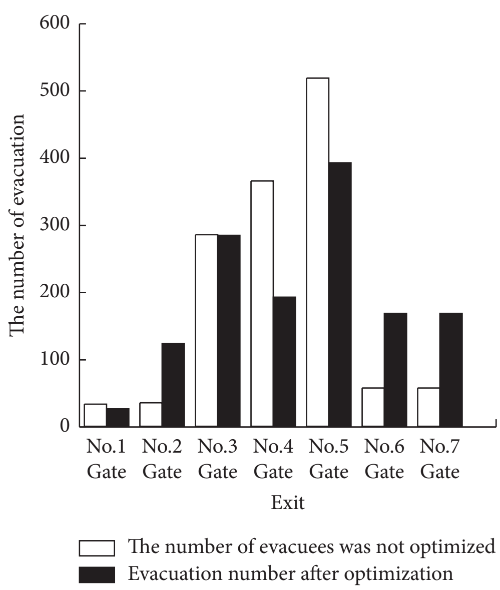

Figure 6: The number of evacuating passengers at each exit before and after optimization.

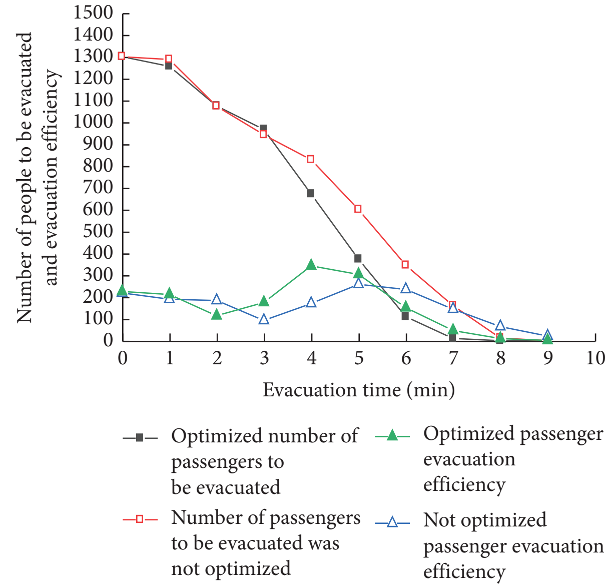

Figure 7: The number of evacuated passengers and evacuation efficiency with time before and after optimization.

before optimization, while the number of evacuees at Gates 2, 6, and 7 is increased, the passengers at the exits with high spatial and temporal congestion are diverted, and the number of evacuation channels becomes more balanced.

The number of passengers to be evacuated and evacuation efficiency curves of the two evacuation methods are shown in Figure 7, where the evacuation efficiency is obtained by fitting the curve of the number of passengers to be evacuated per unit time. The evacuation time is 422 seconds after optimization by the time-varying network algorithm, which shortens the evacuation time by 74 s compared with that before optimization, and the evacuation efficiency is improved by 14%. Analysis of the change curve of the number of evacuees with time shows that the difference between the evacuation effects of the two methods before 3 minutes is not significant; that is, the inflection point appears at 3 minutes, after which the number of evacuees per unit time of the new evacuation method increases, revealing obvious advantages. Analysis of the evacuation efficiency before and after optimization shows that the nonoptimized evacuation efficiency curve exhibits the first inflection point in the second minute because the evacuation efficiency decreases from the second minute due to the congestion at the entrance of the security waiting area; the optimized curve exhibits the first inflection point in the first minute and the second inflection point in the second minute, and the inflection time is earlier and the overall evacuation efficiency is improved.

We summarize the evacuation process in three stages:

(1) Beginning stage: When an emergency occurs, passengers closer to the exit can be evacuated to the safe area quickly without congestion, and the efficiency of passenger evacuation is high.

(2) Congestion phase: In the absence of effective guidance, a large number of passengers in the security checkpoint evacuate according to the shortest path principle, and the evacuation path is unevenly distributed, with a large number of passengers using the same evacuation path, resulting in congestion. After optimization by the time-varying network algorithm, passengers find the exit more quickly under path guidance, unblocking the congestion point and improving efficiency.

(3) End phase: The evacuation of passengers in the terminal building comes to an end, and the remaining passengers are evacuated to the safe area by the evacuation path, and then the evacuation is over.

5. Conclusion

Based on the shortest circuit algorithm, we proposed an optimization method for passenger evacuation in airports. It can perform excellently in evacuation scenarios and significantly shorten evacuation time. The strategy makes the departure hall emergency evacuation more orderly, safe, efficient, and robust. The Shenzhen Bao'an International Airport terminal departure hall was used as a simulation object to verify the effects of the two evacuation methods, and the results showed those as follows:

(1) The extent of the spatiotemporal congestion of passengers in the departure hall's middle area affects the passengers' escape time and evacuation efficiency

(2) The effectiveness of the time-varying network algorithm was evaluated based on the shortest circuit principle. The results show that the proposed strategy can reduce the 74-second-evacuation time and increase 14% efficiency.

(3) The new method can provide a reference and guidance for the development of passenger evacuation plans for large airports

To guide evacuation, we use real-time knowledge of the congestion pattern in the designated area. Then, the individual evacuation plan is implemented through "paperless" departure service software used by passengers, and the optimal evacuation route for each passenger is transmitted to the cell phone software. According to the principle of isotropic evacuation and shortest path, the evacuation paths of passengers to be evacuated do not cross during the evacuation process. In the actual evacuation, evacuated passengers do not necessarily follow the optimal evacuation path, but it can provide a reference for the evacuation decisions of evacuated passengers [30].

The time-varying network algorithm incorporates regional passenger spatial and temporal congestion variables, performs real-time path intervention in the evacuation process, calculates and assigns advantageous paths, develops reasonable evacuation plans for passengers of different spatial and temporal conditions and dynamically guides passengers, which can minimize congestion, reduce overall evacuation time, and improve evacuation efficiency. However, it does not take into account the real-time state of the evacuation network. In the case of an actual evacuation, some source nodes and edges in the network may become impassable. Therefore, how to combine the staged evacuation strategy with dynamic path planning needs further research.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also form part of an ongoing study.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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