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Determining Subway Emergency Evacuation Efficiency Using Hybrid System Dynamics and Multiple Agents

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Abstract: With the rapid development of the city, more and more people are choosing the subway as their travel mode. However, the hidden dangers of the subway are becoming increasingly prominent, and emergency evacuation of the subway has become a key factor for its safe operation. Therefore, the research objectives of this paper were to focus on the subway emergency evacuation hybrid model to fill the gap in the field of emergency evacuation simulation methods and countermeasure optimization. The analysis network process (ANP) was used to analyze the influence factors and weights of subway pedestrian evacuation. On this basis, a multiagent model of subway pedestrian evacuation (SD + multiagent) was developed and simulated. The results show that the comprehensive evacuation strategy could improve the evacuation efficiency, shorten the evacuation time, and avoid the waste of resources. This study not only improved the accuracy of the simulation, but also clarified the evacuation process. This approach can effectively prevent the occurrence of subway accidents, reduce casualties, and prevent large-scale casualties such as secondary accidents (induced secondary disasters).

Keywords: emergency response; safety management; system dynamics; multiagent

MSC: 93A16

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1. Introduction

Public emergency is regarded as the cornerstone of national stability and social tranquility. The traffic volume in major cities is growing rapidly. Whether in open areas or in closed places, if the crowd density is very large, public safety accidents are prone to occur, and the consequences are often very serious. Therefore, public safety and emergency evacuation issues have been given high priority. The statistics [1] of different types of subway emergency accidents in recent years are shown in Figure 1.

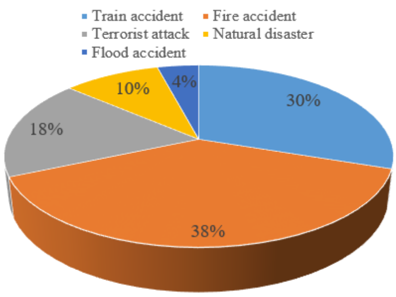

Figure 1. Statistics of subway accidents.

Because of the special characteristics of the subway, the structure of the subway station is more complex. Once an accident occurs in the subway, its consequences are often more difficult to control than ordinary stations (such as bus stations). This brings challenges to the reasonable optimization of subway environmental facilities and the formulation of emergency plans. This paper provides decision support for subway safety management using simulations to reduce the possibility and loss of accidents, which is of great significance to the evacuation of subway accidents.

With the deepening of the research on pedestrian flow and evacuation, more and more researchers are paying attention to research on subway evacuation, such as from the perspectives of the social force model [2], large transfer stations [3], and group dynamics [4]. In [5], the authors performed theoretical calculations and analyzed the evacuation transportation capacity for emergent large passenger flows in different types of subway stations. In [6], the authors studied the impact of two parameters, maximum speed of reaching upstairs and minimum width of the stairs used by each person, on subway operations. Evacuation performance was predicted using the software building EXODUS [6].

In addition to the numerical simulation and theoretical analysis, experiments and questionnaires have also been used to study the characteristics of evacuation behavior of pedestrians, considering factors such as gender, age, knowledge, and companionship. In [7], the authors used the EICI method that coupled chance-constrained programming with an interval integer programming model framework. In [8], the authors discussed the effects of the type, number, and distribution of leaders, as well as guidance strategy, on crowd evacuation based on a multigrid model. An agent-based model prototype was introduced to simulate the behavior of evacuees on subway station platforms in normal and emergency situations [9]. In [10], the authors analyzed the ventilation and smoke exhaust methods of multilayer and complex subways.

Subway evacuation is not only an individual behavior, but also a group behavior. The analysis of the characteristics of different groups is of great significance to the study of subway evacuation. Therefore, a simulation model was established to explore and study the evacuation law of group behavior [11].

The numerical simulation model has become an effective tool to study group behavior evacuation. The social force model is one of the most widely used simulation models for group behavior evacuation. The social force model is a microsimulation model of pedestrian behavior that can be used for evacuation modeling. In addition to the social force model and its evolutions, agent-based simulation models such as the cellular automata model have increasingly been applied in group behavior simulation [12–16].

Various authors simulated emergency evacuation using the social force model and group evacuation to simulate the emergency evacuation [17–20]. In [21], the authors proposed a social field force model (taking the social group as a force field), which was optimized using the artificial bee colony algorithm. A visual parameter was added into the simulation model to prejudge the exit congestion and to help the group by selecting the best evacuation exit. In [22], the authors proposed two different group evacuation (GE) regimes, namely, leaderless GE and leadership GE, to explore the evacuation dynamics of group-structured pedestrians. In [23], the authors studied crowd tangential change behaviors and their mutual processes, as well as revealed the relationship between the tangential change behaviors and the crowd density, thus providing a theoretical basis for multichannel evacuation organizations and expanding the theoretical space for evacuation crowd dynamics. In [24], the authors used experimental simulations to study the effects of group size, expected speed, exit width, etc. on the overall evacuation performance and local group behavior.

According to the current research status, it can be found that a large number of research results have been obtained in the long-term research on emergency evacuation, with clear research directions. These clear research directions mainly include the analysis of influencing factors of subway emergency evacuation, the simulation analysis of evacuation, and the research of emergency management strategies.

On the basis of these directions, the research goal of this paper was to focus on the subway emergency evacuation simulation and develop an evacuation hybrid model to fill the gap in the field of emergency evacuation simulation methods and countermeasure optimization. This paper investigates and analyzes the urban rail transit transfer stations operated in China, and the stations investigated are concentrated in Beijing and Qingdao. The object of this simulation analysis was the development of an emergency evacuation model of Qingdao Metro in the face of social security events (such as hijacking or terrorist attacks). On this basis, the types of station transfer forms, statistical data, subway station exits, gates, and other infrastructure were analyzed. The passenger data, behavior characteristics, and evacuation management were analyzed.

2. Methods

The pedestrian evacuation factors in the subway were analyzed using ANP (analysis network process, a decision-making method that adapts to the hierarchical structure of non-independence) [25–27]. The environmental facilities of the station, pedestrian factors, and evacuation management were analyzed to identify the factors that influence subway evacuation. Then, an influencing factor system was developed to calculate the weights of the influencing factors. The research process is shown in Figure 2.

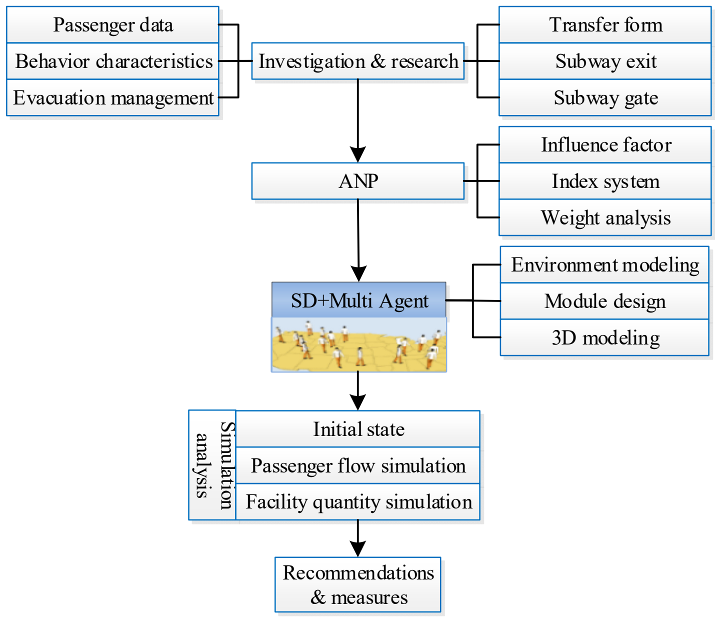

Figure 2. Research process.

The evacuation factors were analyzed to calculate their weights using ANP. Then, the subway emergency evacuation system dynamics model (SD, a quantitative method based on feedback control theory, which can be used in computer simulation to study complex socioeconomic systems) based on multiple agents was established, and the emergency evacuation was simulated and analyzed [28]. Next, simulation analysis was carried out with different strategies, mainly including the initial state, passenger flow, and facility quantity simulation. The best evacuation guidance strategy was obtained by analyzing and comparing the simulation results using different strategies. The simulation results can provide a theoretical reference for the setting and improvement of the emergency evacuation plan.

2.1. Influencing Factors

This paper analyzes the influencing factor system of subway evacuation from the aspects of station environmental facilities, passenger evacuation behavior and subway evacuation management.

(1) Environmental facilities

The evacuation equipment of the station includes the evacuation capacity of stairs and passages [3]. The evacuation capacity, effective width, and the number of entrances and exits will all affect the evacuation [29,30].

(2) Passenger evacuation behavior

Under daily traffic conditions, the age, sex, and health status of passengers vary. Compared with children and the elderly, young people respond more quickly to risks and are more powerful and effective in coping strategies. In contrast, children and the elderly are more prone to panic [31]. Internal factors related to pedestrian evacuation include crowding, herd behavior, and group behavior [32–34].

(3) Subway evacuation management

When an emergency occurs in an urban rail transit station, entrance and exit passageways, platform safety doors, employee passageways, and even escalators may become pedestrian evacuation facilities [2,9,31]. Passenger flow is the main object of emergency evacuation. In order to achieve the expected effect of emergency evacuation, the evacuation speed of pedestrians should be taken as the research basis.

2.2. Indicator System

The factors of environmental facilities and equipment, passenger evacuation behavior, and evacuation management were analyzed during the evacuation process. The above factors are divided into three primary indicators and nine secondary indicators. Environmental facilities and equipment indicators include the number of gates, width of stairs, and width of the entrance and exit. Passenger evacuation behavior indicators include the composition of passengers, physical condition of passengers, and psychological factors of passengers. Evacuation management indicators include the operation plan of the subway, evacuation guidance measures, and safety training for staff. The structure of influencing factors is shown in Figure 3.

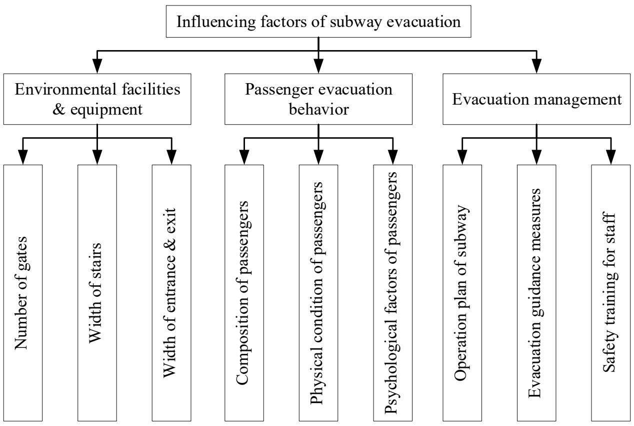

Figure 3. Index system of influencing factors for subway evacuation.

2.3. Index Importance Analysis

The subway pedestrian evacuation factors in this paper were analyzed using ANP. The index system was established according to the factors of subway evacuation in Figure 3. The weight of each index was calculated using super decisions, thus providing a reference and theoretical basis for the later simulation parameter setting.

(1) Consistency inspection

The basic data were scored using a 1–9 scale method, combined with a literature review [35,36]. All factors were compared with each other to form a judgment matrix. The data came from expert scoring. This paper invited 11 experts to score, including two professors, two associate professors, one subway design engineer, two subway administrators, and four subway guides. The judgment matrix was used to determine the correlation degree and importance of factors, which is the basic step of ANP calculation.

According to the calculation method of ANP, a super matrix was automatically generated in the super decision software, as shown in Table 1, revealing the processing results of experts scoring on the scale of 1–9. It was used to calculate the limit matrix and then calculate the weight of relevant indicators.

The calculation process is shown in Figure 4. Firstly, the unweighted super matrix function of super decision was used (click computation, unweighted super matrix, and text in order). Then, the weighted super matrix function was used (click computation, weighted super matrix, and text in order). Next, the limit matrix function was used (click computation, limit matrix, and text in order). Lastly, the weighting of indicator functions was used (see Table 2).

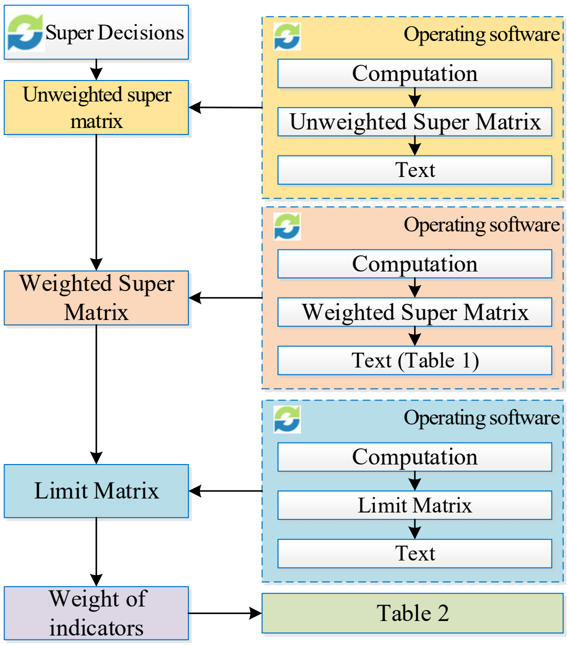

Figure 4. Calculation process of index weight.

The index system is the main factor influencing the evacuation efficiency. The index system was quantified, and the ANP model was used. Then, the weight of each index was calculated, providing background programming logic for the construction of subsequent multiagent model. The error of the judgment matrix should be within the normal range according to the consistency test of the constructed judgment matrix, i.e., *Inconsistency* < 0.1, as shown in Equations (1) and (2). In this paper, we tested the consistency of all judgment matrices in turn, met the standard of consistency test, and ensured the reliability of the obtained index weights.

$$CI = \frac{\lambda_{max} - n}{n - 1}, \tag{1}$$

$$CR = CI/RI, \tag{2}$$

where *CI* is the consistency index, λ_{max} is the maximum eigenvalue of the judgment matrix, n is the number of compared factors, *CR* is the consistency ratio, and *RI* is the average random index.

Table 1. The super matrix.

Cluster Node Labels		Passenger Evacuation Behavior A_1			Evacuation Management A_2			Environmental Facilities and Equipment A_3		
		Personnel Ratio X_1	Physical Conditions X_2	Psychological Factors X_3	Operation Organization Plan X_4	Evacuation Guidance Measures X_5	Coach Training X_6	Number of Gates X_7	Stair Width X_8	Entrance and Exit Width X_9
Passenger evacuation behavior A_1	Personnel ratio X_1	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.148408	0.183108	0.066848
	Physical conditions X_2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.039264	0.032430	0.092836
	Psychological factors X_3	0.000000	0.000000	0.000000	0.000000	0.136994	0.136994	0.062328	0.034462	0.062922
Evacuation management A_2	Operation organization plan X_4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.084393	0.000000	0.156070
	Evacuation guidance measures X_5	0.000000	0.000000	0.000000	0.250000	0.000000	0.000000	0.531642	0.562500	0.218351
	Coach training X_6	0.000000	0.333333	0.000000	0.750000	0.000000	0.000000	0.133965	0.187500	0.208702
Environmental facilities and equipment A_3	Number of gates X_7	0.626696	0.366630	0.327480	0.000000	0.000000	0.000000	0.000000	0.000000	0.045820
	Stair width X_8	0.093616	0.160141	0.259921	0.000000	0.215751	0.431503	0.000000	0.000000	0.148451
	Entrance and exit width X_9	0.279688	0.139896	0.412599	0.000000	0.647255	0.431503	0.000000	0.000000	0.000000

(2) Determination of index weight

The stability weight of each index was calculated using the special ANP calculation software super decision [37], and the calculation process is shown in Figure 4. The obtained stability weights are shown in Table 2.

According to the results, the weights were arranged in descending order. Therefore, it can be considered that the factors at the top of the order are the most influential factors in the process of pedestrian evacuation in an emergency subway accident. In the evacuation simulation design, the parameters of these indicators should be set for the subway to improve the evacuation efficiency.

Table 2. Weights of influencing factors.

Firstly Index	Secondary Index	Local Weight	Comprehensive Weight
Passenger evacuation behavior A_1	Personnel ratio X_1	0.49065	0.07841
	Physical conditions X_2	0.11367	0.018166
	Psychological factors X_3	0.39567	0.063231
Evacuation management A_2	Operation organization plan X_4	0.11664	0.045432
	Evacuation guidance measures X_5	0.57856	0.225352
	Coach training X_6	0.3048	0.11872
Environmental facilities and equipment A_3	Number of gates X_7	0.16976	0.076507
	Stair width X_8	0.28075	0.126533
	Entrance and exit width X_9	0.54949	0.247649

2.4. Model

2.4.1. Physical Environment Modeling

According to the pedestrian simulation SD model and the subway pedestrian evacuation simulation requirements, the movement of outbound passenger flow in the subway was simulated. The main steps included the establishment of the evacuation mathematical model, the loading of the base map, environmental modeling, and logical modeling.

(1) Evacuation mathematical model

The evacuation model of station stairs is as follows [37,38]:

$$C_s = N_s \sum (B_s - b_s) t_{eva}, \tag{3}$$

where C_s is the evacuation capacity of station stairs, N_s is average flow up and down the stairs (number/m·s), B_s is the width of the stairs (m), B_s is the distance between the handrail and wall (m), and t_{eva} is the evacuation time of pedestrian flow (s).

$$C_p = N_p \sum (B_p - b_p) t_{eva}, \tag{4}$$

where C_p is the evacuation capacity of pedestrians, N_p is average flow of pedestrians (number/m·s), B_p is width of the channel (m), and b_p is the width of the channel edge and wall (m).

The evacuation capacity of the gates is shown in Equation (5).

$$C_g = \frac{nFt_{eva}}{60}, \tag{5}$$

where C_g is the evacuation capacity of the gates, n is the total number of pedestrian exit gates, and F is flow rate of pedestrian leaving the gate (number/min).

The effective width and the number of entrances and exits are related to personnel evacuation [39–41]. The evacuation capacity of entrances and exits is shown in Equation (6).

$$C_e = N_e (B_e - b_e) t_{eva}, \tag{6}$$

where C_e is the evacuation capacity of entrances and exits, N_e is the average pedestrian flow at the entrance and exit during evacuation (number/m·s), B_e is the width of the entrance and exit (m), and b_e is the boundary width of the entrance and exit (m).

(2) Loading the base map

The base map file of the subway platform layer was loaded into the software Anylogic [42]. In order to match the size of the base map with the size in the modeling environment, a scale was used in this step.

(3) Environmental modeling

Environmental modeling included the drawing of walls, target lines, escalators, etc. The wall was selected to be in the pedestrian garage. At the end of the drawing, the parameters such as color and transparency were set uniformly. After drawing the target line, the escalators, stairs, and turnstiles were further set up, as shown in Figure 5.

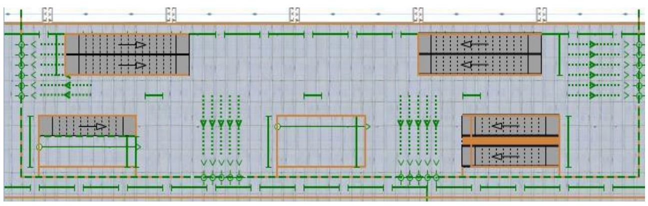

Figure 5. Environment model establishment of subway station.

The modeling data comes from the CAD drawings and related information provided by the subway station. There are five entrances and exits on the station hall floor, and passengers can purchase tickets and check the safety from the five entrances and exits. According to the flow data obtained from field research, it was set that the sending passenger flow at the peak of passenger flow reached 4800 persons/h.

2.4.2. Agent Module Design

This paper was based on AnyLogic [43] for the secondary development, assigning the person class to the judgment logic structure in the model, and selecting the evacuation and shortest path.

Multiagent designs have the advantage of self-organization, which can realize self-management and get rid of the influence of additional constraints. They also have social attributes, and social law restricts the behavior law of agents. In addition, agents can use code to establish associations, which is convenient for secondary development. Multiple intelligence physical fitness can properly describe the pedestrian characteristics in subway evacuation. Therefore, this paper uses a multiagent design to represent pedestrians, with a visual simulation operation interface, thereby forming a more intuitive and real 2D and 3D animation.

(1) Pedestrian evacuation logic modeling

On the basis of ANP analysis, a system dynamics (SD) model, as shown in Figure 6, was established to investigate the impact of each index on the evacuation. The meaning of variables in the figure is listed in Table 2.

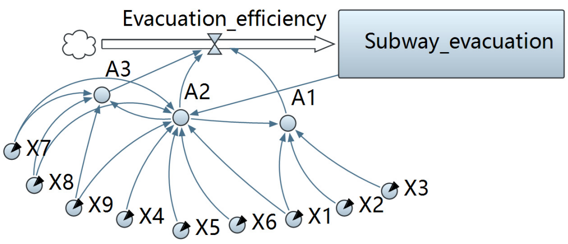

Figure 6. SD model.

Passenger evacuation behavior A_1 is not only affected by X_1–X_3, but also positively affected by evacuation management A_2. The subway management factors are affected not only by X_4–X_5, but also by the personnel ratio X_1. Because the personnel ratio is different, the evacuation efficiency is different, and the management measures are slightly adjusted. X_7–X_9 are also the main factors affecting the metro management measures. In addition, there was a feedback relationship between the subway evacuation effect and the subway management factors. The evacuation effect is helpful to evaluate the effect of Subway Emergency Management, and it can provide an evaluation basis for the next adjustment of management measures. The unit of measurement of X_1 is a percentage (%), that of X_2 and X_3 is a qualitative value (1—unhealthy, 2—sub-healthy, 3—healthy), that of X_4, X_5, and X_6 is a qualitative value (1—poor, 2—average, 3—excellent), that of X_7 is a number, that of X_8 and X_9 is m, and that of subway evacuation is density (people/m^2). It is the integral of time T, and the simulation criterion is the personnel density of the subway station per second.

The stock is subway evaluation, the auxiliary variables are A1–A3 (passenger evacuation behavior, evacuation management, and environmental facilities and equipment), and the flow is the evacuation efficiency, as shown in Figure 6 [44].

The feedback relationship between subway evacuation and A2 (evacuation management) is shown in Figure 6. The evacuation management measures are further adjusted according to the evacuation effect after being implemented for a period of time, which is a process of continuous improvement. A2 and A3 (environmental facilities and equipment) also have a feedback relationship, and equipment and facilities are fine-tuned according to the needs of management measures. In addition, the situation of equipment and facilities is also considered when formulating management measures.

The simulation of the evacuation is complex, including the analysis of the delay process. The implementation of evacuation management (A2) is slightly later than that of passenger evacuation behavior (A1) and environmental facilities and equipment (A3) in daily operation and maintenance. In other words, evacuation management is delayed. When the passenger evacuation behavior (A1) or environmental facilities and equipment (A3) change to cause a poor evacuation effect, the evacuation management (A2) is changed accordingly. In this paper, SD is used to express the feedback relationship and delay of various factors to more clearly analyze the subway evacuation effect and study management measures.

Model validation included two steps. One was to invite experts to analyze the factors in the model and their relationship to demonstrate whether they are reasonable. The second was to conduct a pre-simulation, i.e., input the parameters of the known results for simulation, and determine whether the simulation results are consistent with the preset results. If they are consistent, the model can be considered reliable; otherwise, the model needs to be revised, as shown in Figure 7.

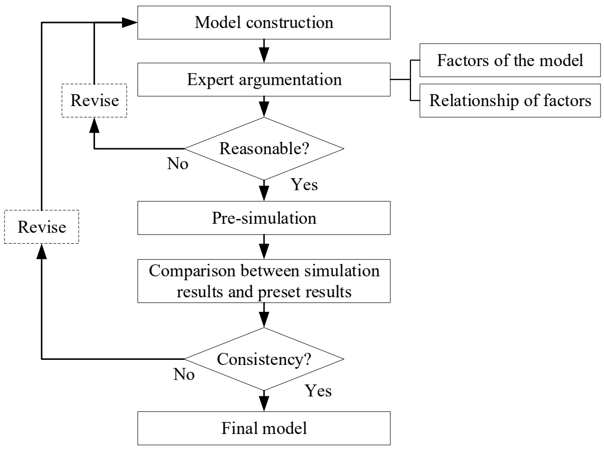

Figure 7. Process of model validation.

SD can clearly analyze the dynamic process of subway evacuation, but it cannot reflect the specific information of evacuation, such as personnel distribution and subway environment layout. The multiagent design can clearly display the dynamic information of all equipment and personnel in the subway evacuation process, but its implementation needs the support of background logic. Therefore, this paper used system dynamics to analyze the logical relationship of subway evacuation, and then took the logical relationship as the background operation logic of the multiagent model. According to the analysis of SD, the background logic of the evacuation multiagent model (Figure 8) was developed. There are five entrances and exits on the floor of the station hall. Passengers can purchase tickets and check safety from the five entrances and exits. On the basis of the traffic data obtained from field research, the passenger flow during the peak period was set to 4800 persons per hour. The evacuation module served as the switching point for the passenger flow from the normal state to the evacuation state. Its logic is to ensure that, when an emergency occurs, all passengers in the passenger station immediately stop their behavior leading to the destination and instead find the nearest escape route.

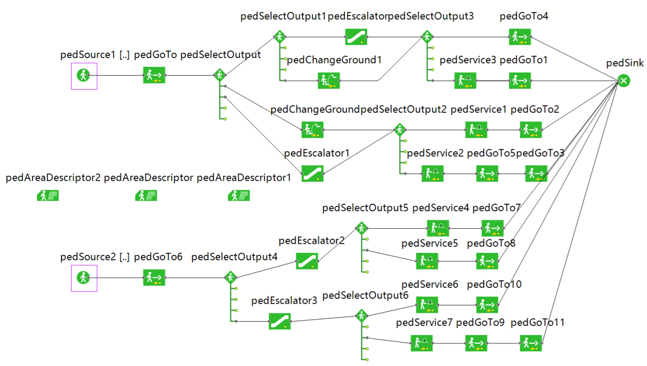

Figure 8. Background operation logic of pedestrian evacuation.

In Figure 8, Ped Source is the pedestrian module information, Ped Go to is the pedestrian path, Ped Escalator is a pedestrian taking the escalator, Ped Change Ground is a pedestrian passing through the stairs, Ped Sink is a pedestrian withdrawing from the station, Ped Service is the queue selection and time delay, Ped Wait is the waiting and waiting time, Ped Select Output is the pedestrian selection behavior, Ped Area Descriptor is the pedestrian area, and Ped Settings is the pedestrian evacuation speed.

The algorithm of maximum pedestrian flow and optimal path was specified [2,36,37], as shown in Equations (7)–(9).

$$L_s = \{L_i | N(L_i) = n_w, (n_w, n_s) = l_s, n_s \in N_j, N_j \in G_s\}, \tag{7}$$

where $N(L_i)$ is the starting point of L_i, N_j is the end point, G_s is the safety range, and L_s is the path set from the end node of the branch to the point G_s in the safety range N_j.

$$L'_s = \{L_i | D(L_i) < D(L_{i+1}) < \ldots < D(L_n), L_i \in L_s\}, \tag{8}$$

where L'_s is the path set, and $D(L_i)$ is the equivalent length of L_i.

The optimal disaster avoidance route is to determine a path $L_{s\,min}$ with the shortest equivalent length at L', as shown in Equation (8).

$$L_{\text{mins}} = \left\{ L_i \middle| D_{\text{mins}} = \sum_{i=0}^{l_i} D(L_i), L_i \in L'_s \right\}, \tag{9}$$

where $D_{\text{mins}}(L_i)$ is the shortest distance for personnel, and l_i is the number of route branches contained in L_i.

The above logic and optimal path planning were integrated into the pedestrian library to create a set of *getNear*. The pedestrian library is a programming function, which covers the parameters transmitted by pedestrians during evacuation. Anylogic supports secondary development; hence, this paper used some programming techniques to improve the reliability and efficiency of simulation. The main attribute codes are as follows:

```
TargetLine tl = new TargetLine();double dis = infinity;
For (TargetLine target:main.collectionNearestLine){
if (dis > this.distanceTo(target.getX(),target.getY())){
tl = target;
dis = this.distanceTo(target.getX(),target.getY());
}}
return tl.
```

(2) Leader role design in the model

In this paper, the role of grooming personnel was added to the model. When pedestrians escape in the subway station, attractors are used to guide pedestrians to escape, which then exit the subway after all pedestrians have successfully escaped.

(3) 3D modeling

Anylogic could be used to further develop and design to build 3D models on the basis of the 2D models. After drawing, the 2D model was obtained. The pedestrian simulation was displayed more realistically through the 3D model, which improved the display ability.

3. Results

3.1. Emergency Evacuation under Normal Conditions

The maximum daily passenger flow of this subway station is about 960 people; hence, the number of evacuated persons in the subway station was set to 963. They were on the platform and hall floors, three of whom were guides, waiting for everyone to evacuate before escaping. The number of gates on the left side of the first floor was set to 5, the number of gates in the middle position was set to 4, and the number of turnstiles on the right was set to 4. In addition, according to the research of the Chinese Academy of Building Sciences on the evacuation speed of the subway during the peak period, the basic parameters of personnel were set as follows: for males, the average initial escape speed of was 1.6–1.8 m/s and the comfortable speed was 1.8–2.1 m/s; for females, the average initial escape speed was 1.3–1.4 m/s and the comfortable speed was 1.4–1.5 m/s [44,45]. It took 272 s to complete the escape. The escape situation in the 2D model is shown in Figures 9–12.

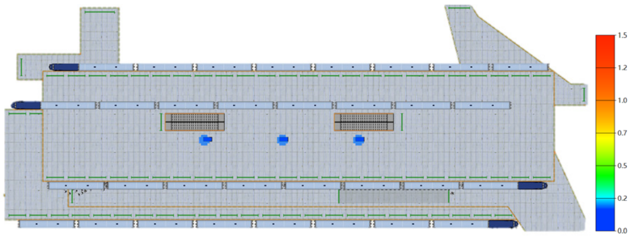

Figure 9. Pedestrian distribution density at 10 s.

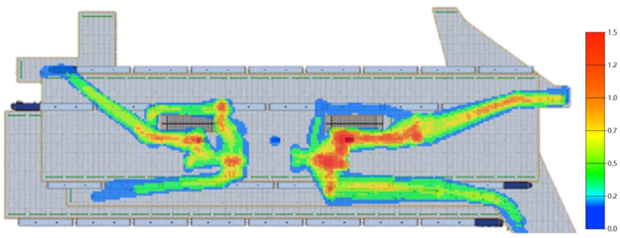

Figure 10. Pedestrian distribution density at 60 s.

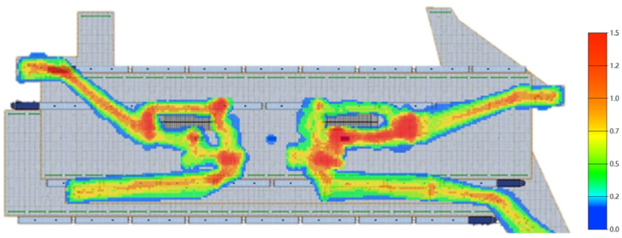

Figure 11. Pedestrian distribution density at 180 s.

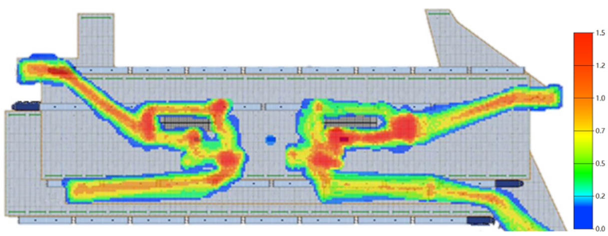

Figure 12. Pedestrian distribution density at 240 s.

The figures show the simulation results of 10 s, 60 s, 180 s, and 240 s. It can be seen from the simulation results that, during the evacuation process, people gathered more seriously at the gate position and at the bottom of the escalator. The results show that, as of 10 s, the crowd density increased gradually as the pedestrians moved to the first floor. Pedestrian-intensive areas also expanded upward. About 60 s later, the pedestrian-intensive area was extended to the first floor. The evacuation situation was compared in the 3D view to more intuitively observe the crowd gathering situation, as shown in Figures 13 and 14.

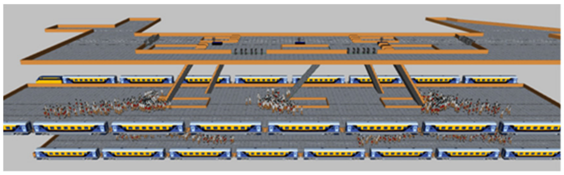

Figure 13. Pedestrian distribution in 3D view at 10 s.

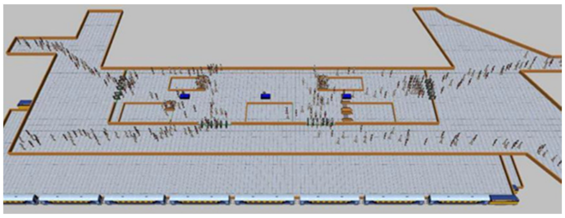

Figure 14. Pedestrian distribution in 3D view at 60 s.

The 3D view shows that, at the beginning of the evacuation (10 s), some pedestrians had just got off the train, while a large number of people on the platform apparently gathered at the entrance of the escalator. Within 240 s, many pedestrians had fled to the lobby floor and apparently gathered at the door. After all pedestrians on the lobby floor fled, the evacuees began to flee the scene.

The above analysis found that the high density of people at the stairs and doorways was the bottleneck factor in the whole evacuation process. Therefore, the influence of different factors on the emergency evacuation speed was analyzed by varying the personnel structures, the width of the evacuation stairs, and the number of gates.

3.2. Passenger Flow Control Strategy

The evacuation capability of the environmental equipment of the subway station was studied to further analyze the evacuation effect. In this paper, the evacuation effect was displayed and measured according to the density of people passing through stairs, gates, and other facilities per second.

(1) Emergency evacuation at different sex ratios

In the construction of pedestrian intelligence, the simulation study of the effect of human structure ratio on pedestrian evacuation was realized by setting different male-to-female ratios.

In the case that 70% of the evacuated pedestrians were women, the average speed of the evacuated persons was 1.42 m/s, and other parameters remained unchanged, the following results can be obtained: the total evacuation time was 284 s, which is longer than the result at the male-to-female ratio of 1:1. The total number of people evacuated was 963, which reached the standard that the evacuation was completed within 6 min. The evacuation result in this situation is shown in Figure 15.

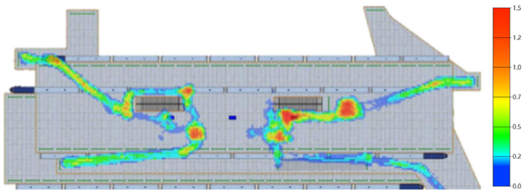

Figure 15. Scenario of 70% female evacuation.

In the case that 70% of the evacuated pedestrians were men, the average speed of the evacuees was 1.85 m/s, and other parameters remained unchanged, the following results were obtained: the total evacuation time was 268 s, which was 4 s shorter than the results at the male-to-female ratio of 1:1 and 18 s longer than the result at the male-to-female ratio of 3:7. The evacuation result in this situation is shown in Figure 16.

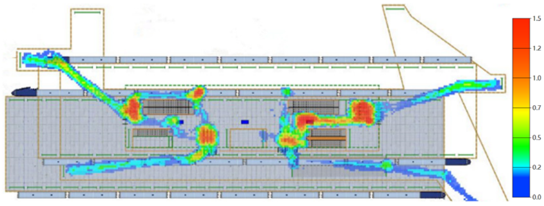

Figure 16. Scenario of 70% male evacuation.

(2) Emergency evacuation with different ages

According to the characteristics of the demographic influences, the average speed of the elderly and children is 0.76.

If adults accounted for 70% of the total evacuated population and the elderly and children accounted for 30%, the following results were obtained: the total evacuation time was 356 s, which is 116 s longer than the initial result, as shown in Figure 17.

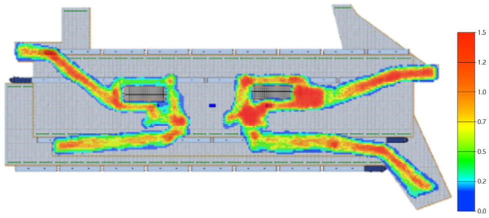

Figure 17. Evacuation of 30% elderly and children.

If the elderly and children accounted for 70% of the total evacuated population and adults accounted for 30%, the following results were obtained: the total evacuation time was 378 s, which did not reach the standard of evacuation within 6 min, as shown in Figure 18.

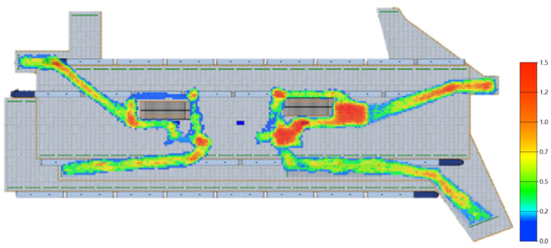

Figure 18. Evacuation of 70% elderly and children.

3.3. Facilities and Passenger Flow Control Strategies

(1) Emergency evacuation with different numbers of turnstiles

In addition to the personnel ratio structure, the number of gates can affect the evacuation time. Thus, the influence of the number of gates on the evacuation was also studied. Firstly, the number of turnstiles and queues on the left side of the hall floor was changed from five to eight. The total number of turnstiles was 16. From the simulation results, the total evacuation time was 250 s, which is 22 s shorter than the normal time.

When the number of turnstiles was increased by three, the evacuation time was less than 20 s. When the number of turnstiles was set to the original number of 13, the population density at the hall floor was as shown in Figure 19. After increasing the number of turnstiles, the population density at the hall floor was as shown in Figure 19. By comparing the population densities at different number of turnstiles, we can observe that the population density with 13 turnstiles began to decline gradually at 50 s, while the population density with the increased number of turnstiles showed a clear downward trend at 26 s. In addition, after 150 s, the population density obviously tended to 0, indicating that the evacuated crowds had gradually left the subway station through the turnstiles to the exits on both sides.

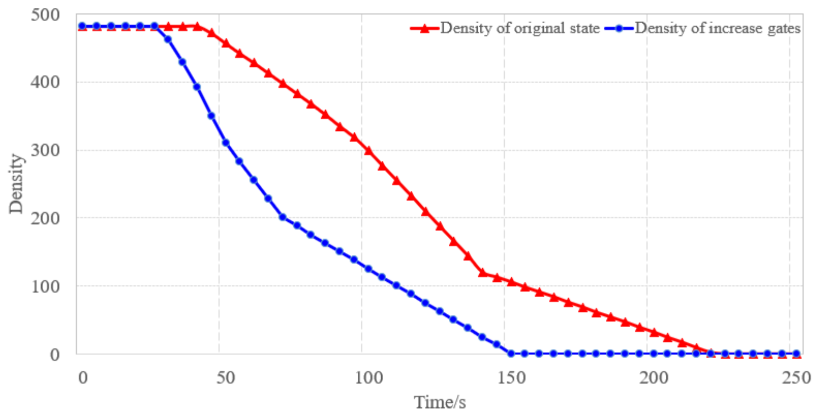

Figure 19. Original evacuation and increasing gates evacuation.

When the number of gates increased to 18 and 20, the evacuation time decreased by 42 s and 47 s, respectively. The evacuation time varied with the number of gates, as shown in Figure 20. There was no large fluctuation in the evacuation time at a later stage. This is because, limited by the moving speed of the crowd and the width of the escalator, although the number of gates increased, the evacuation time of people did not decrease significantly. However, when the number of gates exceeded 20, this resulted in a waste of resources. Therefore, the appropriate number of gates is of great significance for subway management and pedestrian evacuation.

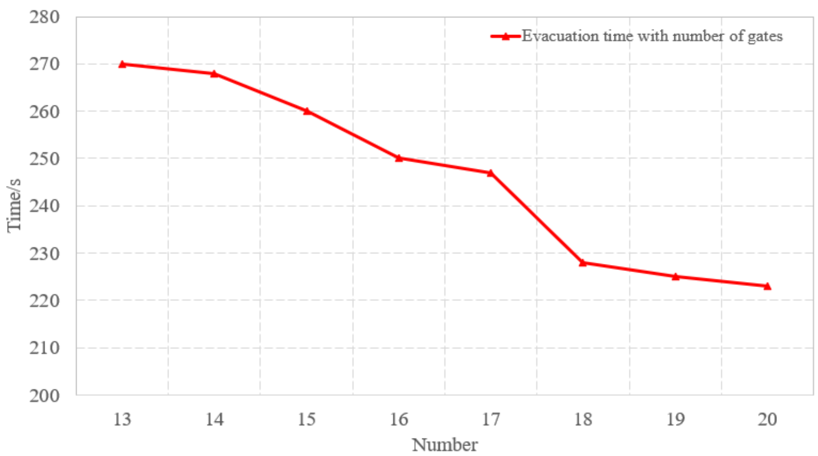

Figure 20. Trend of evacuation time with the number of gates.

(2) Emergency evacuation with different widths of escalator

The width of the escalator also has a certain impact on the evacuation time. The relationship between escalator width and evacuation time is shown in Figure 21.

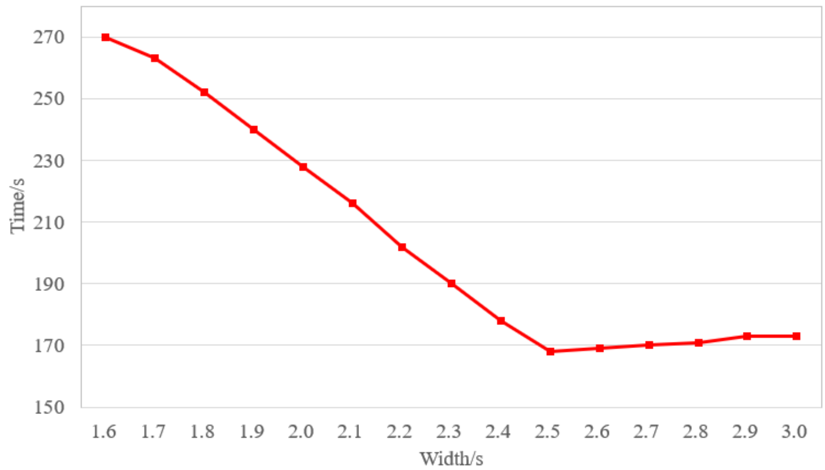

Figure 21. Relationship between escalator width and evacuation time.

It was found that the evacuation time was short when the escalator width was 2.5 m, but the evacuation time was longer when the escalator width was 2.8 m. This is because, at a larger escalator width, the crowd congestion at the exit slowed the evacuation process.

(3) Evacuation with different widths of entrance and exit

The width of the escalator also has a certain impact on the evacuation time. The model had five target lines, located at exit 1A, exit 1B, exit 3A, exit 3B, and exit 4. The following simulation results were obtained at different widths of exits: the original width of exit 1A was 3 m, and the width was increased by 1 m. The original width of exit 3B was 2 m, and the width was increased to 3 m.

It was found that increasing the width of exit could improve the evacuation efficiency and reduce the time to a certain degree. With the increase in the width of the exit, the evacuation time was correspondingly shortened, which also proves the importance of the exit width to the evacuation of subway emergencies.

3.4. Combination Strategy

Taking the escalator width, the number of turnstiles and the width of entrances and exits as a combination strategy, the simulation results obtained were as shown in Figure 22. The digitals (1A, 1B, 2, 3A . . .) in the figure indicate the number of the escape exit.

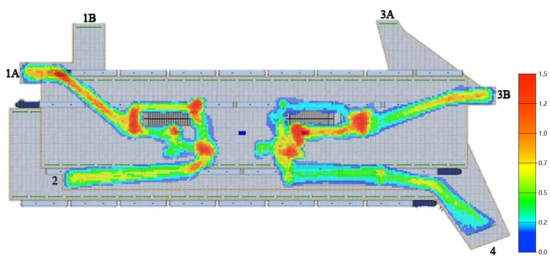

Figure 22. Simulation results of combined strategy.

4. Conclusions

This paper systematically studied the evacuation of subway stations. This research creatively combined ANP with SD and a multiagent design to establish and simulate the evacuation model of subway station. The main conclusions of this paper are as follows:

(1) The risk factors of subway evacuation were investigated, and the weights of each index factor were calculated using ANP.

(2) The subway emergency evacuation model based on SD + a multiagent design was constructed. The facility control strategy based on the passenger microscopic behavior

model was studied from the aspects of adjusting passenger flow personnel, controlling the number of facilities, and controlling the width and public facilities.

(3) The results show that when the elderly and children account for a large proportion (70%), it is necessary to strengthen the guidance of evaluation commanders. If the ratio of gate flow to passenger flow is 1.67–1.88%, the evacuation effect is the best. The evacuation time is shortened when the width of the escalator is increased from 1.60 m to 2.50 m. However, it was increased from 2.50 m to 2.80 m, the evacuation time increased instead. The best evacuation effect could be achieved by synchronously increasing the width of escalators, the number of doors, and the width of exits.

A research method incorporating ANP + SD + a multiagent design proposed in this paper provides a new approach and theoretical basis for emergency response research of the subway and similar transportation hubs. In future research work, we will further explore the optimal countermeasure system for subway evacuation on this basis.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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