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Research Article

Emergency Evacuation Simulation and Optimization for a Complex Rail Transit Station: A Perspective of Promoting Transportation Safety

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Rail transit stations with multifloor structures have been built in many cities to intensively utilize land resources and facilitate lives of community. However, being overcrowded with passengers results in high risks during daily operation. In response, this study conducted an emergency evacuation simulation and optimization in the three-dimensional (3D) space of "complex rail transit stations" (CRTSs). The aim of the paper is to provide a methodology to determine effective emergency evacuation strategies for CRTSs. The Lianglukou Rail Transit Station in Chongqing, China, was used as a case study and the AnyLogic simulation platform employed for simulating emergency evacuations. An emergency evacuation theoretical framework was established. The emergency evacuation strategies, including evacuation routes and evacuation times, were determined based on the theoretical demonstration. Simulation and optimization of emergency evacuation in the Lianglukou station were conducted. Accordingly, four main simulation results were obtained: (1) Escalators/stairs and turnstiles are key facilities in the evacuation; (2) Effective guidance for the evacuation is necessary in the public space of the station; (3) Passenger aggregation nodes should be guided for balanced evacuation; (4) Removing metal barriers is a useful evacuation optimization measure. The proposed research method and framework can be used by other CRTSs in the establishment of emergency evacuation strategies and effective optimization strategies to promote safety of transportation system. The research findings are beneficial to passengers in helping them provide valuable emergency evacuation guidance.

1. Introduction

As a main component of modern transportation, urban rail transit conforms with the principle of sustainable development and has advantages of large capacity, high speed, energy saving, low pollution, convenient, and comfortable [1, 2]. Urban rail transit system could be subdivided into 7 categories, which are tram, light rail, rapid transit, monorail, commuter rail, funicular, and cable car, among which rapid transit includes underground, subway, tube, elevated, and metro (Mass Rapid Transit) [3]. To date, over 200 cities operate metros worldwide [4]. In China, metro and light rail are two major categories of urban rail transit, and over 5761 km of urban rail transit are in operation in 35 cities, ranking the first in the world [5]. The passenger flow volumes are constantly increasing and many rail transit stations have reached, or even exceeded, their designed long-term maximum passenger flow volume [6]. Rail transit stations have become highly populated spaces, especially transfer stations with multirail transit lines. In 2018, the urban rail transit passenger flow volume reached to 21.07 billion in China, with an increase of 2.59 billion (14%) compared to the previous year. The average daily passenger flow volume of Beijing and Shanghai rail transit are 10.54 million and 10.172 million, respectively. In October 2018, the daily passenger volume of Renminguangchang station in Shanghai reached to 0.76 million, which is the maximal value in the station passenger volume record [7].

With the expansion of the rail transit system, rail transit stations are subject to various kinds of potential risks due to passenger overcrowding [8]. Catastrophic accidents occasionally occur. On 10 February 2017, for instance, a Hong Kong metro fire injured 18 people; a Beijing metro elevator accident on 5 July 2011 killed 1 and injured 27 people; and a 19 February 2003 Daegu metro fire caused 198 deaths and 147 injured, to name just a few. The accidents not only influence the operation of one station, but also the whole rail transit transportation network, even the whole city. Emergency evacuation study is therefore a key issue to be considered to help guarantee the safety of rail transit stations.

In recent years, rail transit stations with multifloor structure and different functions integrated in 3D spaces have been built in a variety of Chinese cities, such as Beijing, Shanghai, Guangzhou, Chongqing, Chengdu [9, 10]. These stations consist of many spatial components, including various kinds of physical facilities, passengers, station staff, etc. [11] Complex relationships, that could be conceived as complex systems, also exist among different spatial components [12]. In this study, such stations are termed as complex rail transit stations (CRTSs). This study establishes a theoretical emergency evacuation framework of CRTSs by fully considering the structural complexity of the station. Based on the theoretical framework, the Chongqing Lianglukou rail transit station is used as a case study for modelling emergency evacuation with the AnyLogic simulation platform. The study is to identify a reasonable and efficient emergency evacuation route for pedestrian evacuation, which could provide reference for the safe operation of CRTSs.

2. Literature Review

Emergency evacuation was emphasized as an important task in building design [13, 14]. Evacuation routes, exits, stairways, passages, and turnstiles in rail transit stations are recognized as key facilities that directly influence evacuation route plans [15]. A crowd-aware environment design tool was proposed to analyze the optimal crowd flow-density relationships between crowd and environment [16]. The average minimum width of staircase of per person and the maximum upstairs speed were emphasized as two key parameters affecting the simulating evacuation [17]. A comprehensive study was made for the standard-based occupant evacuation design of Chinese metros, including evacuation to safe areas, evacuation time, and evacuation route [18]. A dynamic route planning problem in a restricted space evacuation was investigated through a heuristic algorithm [19]. Four crucial theoretical issues on the passengers' evacuation are included, which are competitive vs. cooperative behaviours, proactive vs. reactive behaviours, route/exit choice, and symmetry breaking [20]. Pedestrian behaviours and their interactions in crowds were modelled, and particular interests are the self-organized patterns of motion and crowd exit-choice behaviours [21]. Taking into account the complex interactions between traffic and pedestrians, a systematic simulation-based multiattribute decision approach to route choice planning was developed and the uncertainties underlying pedestrian behaviours during an evacuation were modelled [22]. The main reasons and definitions of the crowd shockwave were proposed to study the correlation between people of different densities and stamping accidents [23]. The movement trajectory of pedestrian's evacuation was focused under specific conditions (low visibility) [24]. The mechanism of buffer zone was studied to analyze the effects of different buffer zone lengths on evacuation time, density, pedestrian waiting time, and expected speed [25]. The movement characteristics of the mixed population and the wheelchair users at different widths of evacuation route were studied [26]. In the condition of shooting range fire, the effects of occupant response times and flame spread rate on emergency evacuation were studied [27].

Various emergency evacuation simulation approaches were proposed. A multiagent-based model was developed based on meta model for pedestrian simulation in metro stations and the model includes the three-level pedestrian agent model, the station environment abstraction model, and interactive rule base [28]. The evacuation time for a given number of evacuees was calculated with a multiagent-based simulation approach, while the evacuation bottlenecks in metro stations were also identified [29]. A theoretical framework for safety analysis of underground space was established based on previously reported fire accidents and empirical research into underground stations [30]. Besides, the waiting time during emergency evacuation in crowded transport terminals was studied through two evacuation models built by EXODUS and SIMULEX [31]. Different scenarios for simulating evacuations were considered based on insights from passenger behaviour surveys and a thorough psychological analysis of passengers [32]. Additionally, by combining 3D modelling with the agent modelling method, a multistandard ranking framework was established to quantitatively evaluate the evacuation factors affecting multistory buildings [33]. Combining evacuation exit modelling with agent-based simulations, the fire safety assessment of underground nuclear physics was conducted [34]. Path selection and evacuation strategies in case of complete or incomplete evacuation information were compared based on social force model [35]. An event-driven agent-based approach was proposed to model the fire emergency problem of ultra-high-rise elevator building [36]. The arching effect during emergency evacuation was studied for the university canteen, and the evacuation sequence of each channel is determined based on the principle of minimum evacuation time [37].

The structure characteristics of buildings have already been considered in the existing studies. In the ultra-high-rise building studies, the important role of refuge floor was emphasized. The elevator evacuation was a hot research topic for high rise buildings and was investigated by developing elevator evacuation models [36, 38]. A joint parameter modelling of building and crowds was established to study the density, path traces, speed in different activities and different crowd configurations [39]. The interactive system for computer-aided design optimization was contributed to improved building layouts [40]. Taking the mass rapid transit station as an example, the evacuation simulation process in the high rise building is divided into five stages and seven scenarios, which were analyzed with parameters, including walking speed, coefficient of flow rate, etc. [41]. The existing evacuation studies on the multifloor structure mainly concentrate on the high-rise buildings and most of the buildings are residential buildings or office buildings. These kinds of buildings show the features of multifloor and small public space on every floor. Only a few of research focus on the CRTSs. These kinds of buildings generally have less than 10 floors, large public spaces in every floor, and complex connections among different spatial components.

The above studies provide useful references for rail transit station emergency evacuation research in the aspects of physics structure deconstruction, pedestrian behaviours consideration, route choice, method choice, etc. Based on the existing studies on emergency evacuation, this research innovatively focuses on the emergency evacuation with considering the complex structure characteristics of the rail transit stations.

3. Materials and Methods

3.1. Characteristics of CRTSs. The mainly considered characteristics of CRTSs are multifloor structure and multitypical facilities in the space, which impact the inner space emergency evacuation directly and be the base of the emergency evacuation research. These two characteristics could be obtained and described clearly through field investigations. Thus, field investigations were conducted for some CRTSs, including the Xizhimen station in Beijing, the Hongqihegou station and the Lianglukou station in Chongqing, to clarify the structures and components of CRTSs.

3.1.1. Multifloor Structure of CRTSs. A multifloor structure can help satisfy the transfer demand from different rail transit lines. This generally includes platform floors and concourse floors. Beijing's Xizhimen station, for example, is the transfer station for Lines 2, 4, and 13, and contains 6 floors comprising 3 platform floors and 3 concourse floors. The Chongqing Lianglukou station is constructed in 4 floors, of which B2 and B3 are concourse floors, while B4 and B5 are platform floors. The different floors are connected by 6 escalators/stairs.

3.1.2. Typical Facilities in CRTSs. (1) Escalators/stairs. Escalators/stairs provide vertical connections to different floors in 3D space. In emergency conditions, people on the platform floor should firstly go by the escalators/stairs to the concourse floor. All escalators from the platform to the concourse floor should be kept in operation, while the escalators in the opposite direction should stop operation and be used as fixed stairs, or reverse to the opposite direction [11]. The carrying capacity of the escalators/stairs is directly affected by their physical attributes, including width, length, gradient, and number, which should meet the requirements of an emergency evacuation [36].

(2) Turnstiles. Turnstiles are installed on the concourse floors and connect the CRTSs' inner space to the outside environment. Generally, more than one turnstile is set in the concourse floor to meet the passengers' different trip demands. The turnstiles are automatic ticket checkers in daily operation, but should be opened thoroughly for evacuation in an emergency. The capacity of the turnstiles is determined by their number and width, which should be designed based on the prediction of the passenger flow volume in daily operations and emergency evacuation. The turnstiles should also be clearly labelled in all directions to provide guidance to passengers.

(3) Screen doors. Screen doors in every platform floor are used to separate the platform and train operation area. The screen door area is always a concentration point of passenger flow for it directly connects to the passengers' waiting area. Screen doors should be completely opened for evacuation in the event of an emergency.

(4) Metal barriers. Metal barriers are used on both the platform floors and concourse floors to split large volumes of passengers and guide the directions of passenger flows. They are placed in the screen door area or in front of the escalators/stairs to avoid crowding. Their adjustment should be considered in the event of an emergency to prevent becoming a bottleneck during an evacuation.

3.2. Case Study

3.2.1. Task. The selected study site should have representativeness for the CRTSs. The existing emergency simulation studies emphasis on crowded passengers, while this paper mainly focuses on the complex structure characteristic of the rail transit station. Accordingly, the study site should meet 3 criteria, that (1) daily crowded passengers, (2) complex multifloor structure (more than 2 floors), and (3) occupying with more than one rail transit lines.

3.2.2. Study Site. The Lianglukou rail transit station in Chongqing, China conforms to the above 3 criteria. By December 2018, a total of 10 lines are in operation in Chongqing, incorporating 178 stations and 13 transfer stations [42]. Of the 13 transfer stations, the multifloor complex Lianglukou rail transit station is the transfer station for Line 1 (metro line) and Line 3 (light rail line), which occupy some distinctive stations, including 5 commercial centers, 3 railway stations, and the Chongqing airport. This, together with Chongqing's 2018 urban population of 20.32 million, has led to an extremely large volume of transfer passengers, with a daily average of nearly 170,000 people in the 4 floors of the Lianglukou station [43], making the provisions for emergency evacuation of vital importance.

3.2.3. Variables of the Site. Five field investigations were conducted of the station to clarify its complex structure and obtain the passenger aggregation nodes for every floor. The station contains 4 floors: B2, B3, B4, and B5 floor. The investigation found high-density passenger volumes to be mainly concentrated on B3, B4, and B5. B3 is the concourse floor and includes 4 turnstiles, which connect to exits 5, 6, and 7, and unified exit 1–4 (the independent exits 1, 2A, 2B, 3, and 4 are on B2 floor). B4 is the platform floor of Line 1, with 24 screen doors on each side of the platform and hence a total of 48 screen doors. B5 is the platform floor of Line 3, with 16 screen doors on each side and hence a total of 32 screen doors. B3, B4, and B5 are interconnected with a total of 5 escalators/stairs. Some metal barriers are used on each floor to guide the directions of passenger flows. The dimensions of the three floors were also measured as part of the fieldwork (Table 1).

3.3. AnyLogic Simulation Platform. The emergency evacuation simulation for the 3D space of the station was carried out using

Table 1: Dimensions of the Lianglukou station.

Floor	Length (m)	Width (m)	Area (m^2)
B3	103.8	15.0	1557
B4	96.0	12.0	1152
B5	107.4	12.0	1289

the AnyLogic simulation platform, which was developed in St. Petersburg, Russia, a forward-looking simulation software based on the Java programming language and social force model, which can simulate the evacuation process of the crowd during emergency evacuation. The platform shows the characteristics of visibility, interactivity, and capacity of excellent analysis and optimization, which provides a rich animation of model execution and handles randomness. A virtual prototyping environment for large and complex systems with continuous, discrete, and hybrid behaviour is also provided [44]. The platform is suitable for complex system modelling within a random environment and to identify optimal operational strategies of system control based on risk analysis [45].

The platform consists of autonomous adaptive objects called "agents." An agent exercises its autonomy through actions in the situated environment. The 3 essential characteristics of "agents" in the agent-based modelling are: (1) An agent is a self-contained, modular, and uniquely identifiable individual; (2) An agent is autonomous and self-directed. Agents' interactions generate information, which influence the agents' actions. For example, to avoid collisions with other agents, agents may choose accessible routes rather than the shortest route, and also, may chose accessible exits rather than the closest exit in the emergency evacuation; (3) The state of agents vary over time and the behaviours of agents are conditioned on the state [46].

The simulation follows four steps:

(1) Establishment of the physical space. The facility module and waiting area module are set to simulate the physical space. The facility module includes trains, escalators/stairs, screen doors, turnstiles, security inspection equipment, ticket counters, etc. The waiting area module is the area used by passengers waiting for trains, and includes such facilities as columns, metal barriers, passages, etc.

(2) Definition of passenger agent behaviours. The passenger agent behaviours include taking escalators, using stairs, waiting for trains, distributing in different areas, and choosing evacuation routes.

(3) Programme editing. Based on the Java programming language, the simulation programme was edited. Such as formula "inject( )" is invoked by the command "passSouceOutBoard.get(i).inject( )" to set passengers in physical space. For example, 50 passenger agents are set through every screen door by the targetline setting "collectionDoor.get(index)," which means the set number of passenger agents going through every screen door is 50. The index denotes every specific door, such as targetlinedoor 1, targetlinedoor 2, … etc.

(4) Operation and analysis of the simulation.

3.4. Social Force Model. The social force model was used as the crowd steering technique in this paper and be the base of AnyLogic simulation platform. The walking speed of evacuees in this model is driven by the motive force, the interaction among the evacuee, and the inter-action forces between the evacuee and obstacles.

The social force model is shown as follows,

$$m_i\left(\frac{dv_i}{dt}\right) = m_i\left[v_i^0(t)e_t^0(t) - \frac{v_i(t)}{\tau_i}\right] + \sum_{j\neq i} f_{ij} + \sum_{w} f_{iw} + \varepsilon. \quad (1)$$

In this model, m_i is the quality of agent i; v_i^0 is the desired velocity of agent i; $e_t^0(t)$ is the direction of desired speed of agent i; $v_i(t)$ is the actual velocity of the agent i; τ_i is the relaxation time of agent i; and f_{ij} is the interaction forces from others exerted on agent i; f_{iw} is the interaction forces from walls exerted on agent i.

f_{ij} is the interaction force between the agent i and agent j:

$$\begin{aligned} f_{ij} =& A_i\exp\left[\frac{\left(\left|r_{ij} - d_{ij}\right|\right)}{B_i}\right]n_{ij} \\ &+ kg\left(r_{ij} - d_{ij}\right)n_{ij} + \kappa g\left(r_{ij} - d_{ij}\right)\Delta v_{ji}^t t_{ij}. \end{aligned} \quad (2)$$

This function describes the psychological tendency of two agents by a repulsive interaction, where A_i and B_i are constants. Pedestrian i and pedestrian j keep a certain distance. d_{ij} denotes the distance between the pedestrians' centers, and n_{ij} is a normalized vector pointing from pedestrian j to i. The pedestrians touch each other if their distance d_{ij} is smaller than the sum of their radius. In this case, the model assumes two additional forces inspired by granular interactions, which are essential for understanding the effects in dense crowds: $k\left(r_{ij} - d_{ij}\right)n_{ij}$ counteracting the body compression and $\kappa\left(r_{ij} - d_{ij}\right)\Delta v_{ji}^t t_{ij}$ impeding the relative tangential motion if pedestrian i comes close to j.

f_{iw} is the interaction force between the pedestrian i and the wall w, and the formula is similar as f_{ij}:

$$\begin{aligned} f_{iw} =& A_i\exp\left[\frac{\left(\left|r_{ij} - d_{ij}\right|\right)}{B_i}\right]n_{ij} \\ &+ kg\left(r_i - d_{iw}\right)n_{iw} + \kappa g\left(r_{ij} - d_{iw}\right)\left(v_i \cdot t_{iw}\right)t_{iw}. \end{aligned} \quad (3)$$

ε is a small random force. Its size follows the normal distribution and direction is perpendicular to the direction of velocity [25].

4. Theoretical CRTS Emergency Evacuation Framework

The theoretical emergency evacuation framework consists of emergency accidents, accident spots and evacuation routes, evacuation time, and walking speed [47, 48]. The four aspects are necessary and essential to the emergency evacuation planning and implementation. The emergency accidents are the background or scenarios of the evacuation. The accident spots and evacuation routes are key elements for the evacuation

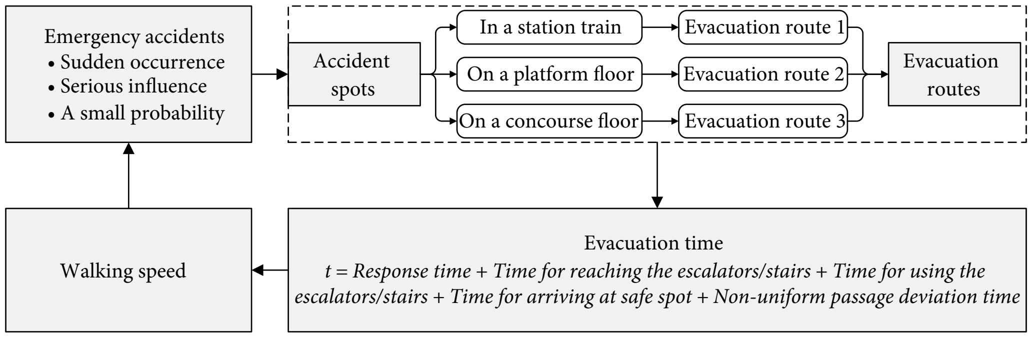

Figure 1: Theoretical CRTS emergency evacuation framework.

planning and practice guidance. The evacuation time calculation method is necessary for the assessment/validation of the evacuation simulation. The walking speeding is a significant variable for the evacuation time calculation and the whole evacuation simulation process. Combined with the general characteristics of CRTSs, the 4 aspects of the framework were applied to the CRTSs emergency evacuation. The framework is shown in Figure 1.

4.1. Emergency Accidents. Past episodes indicate that public safety accidents provide a heavy threat to CRTSs. The main types of public safety accidents are fire accidents, terrorist attacks, and poison-gas accidents [49]. The common features are sudden occurrence, serious influence, and a small probability [50]. These public safety accidents are mainly considered in this research.

4.2. Accident Spots and Evacuation Routes. Emergency accidents can happen in different spots of the station. These involve three main situations: (1) emergency accidents in a station train (a train in emergency accident stopped at the station), (2) emergency accidents on a platform floor, and (3) emergency accidents on a concourse floor. When an emergency accident happens, the station enters an emergency state, and passengers need to be evacuated immediately. The emergency routes of the first situation are with the longest distance. In this situation, passengers firstly escape from the train and then go through the screen doors, platform floor, escalators/stairs, concourse floor, turnstiles, and finally to a safe spot outside the station. In the second situation, when accidents happen in the platform floor area, passengers should use the escalators/stairs, arrive at the concourse floor, and then go to the turnstiles to reach the station's exits. In the third situation, when accidents happen in the concourse floor area, people go directly to the turnstiles. If the emergency accident happens near a turnstile, the emergency evacuation route has two conditions. One is that people directly escape from this turnstile providing the turnstile is opening and available for escape. The other is that people run to other turnstiles to exit the station.

4.3. Evacuation Time. Based on observation and analysis of the passengers' behavioural features, the evacuation time is considered to comprise 5 parts, and they are listed as follows.

4.3.1. Response Time. The response time is preaction time, which is the time from the occurrence of an accident to starting an escape action. According to the illustration in literature [11], the response time is considered 1 min.

$$t_1 = 1\,\text{min}. \tag{4}$$

4.3.2. Time for Reaching the Escalators/stairs.

$$t_2 = \frac{L_s}{v}, \tag{5}$$

where L_s denotes the distance from the farthest point to the escalators/stairs and v is the passenger walking speed. It is easy for people to find out escalators/stairs when going out of the screen doors. In emergency evacuation, people may go by the farthest escalator/stair rather than the nearest one due to crowding.

4.3.3. Time for Using the Escalators/stairs.

$$t_3 = \frac{\left(N_t + N_p\right)}{c}, \tag{6}$$

where N_t denotes the number of train passengers and N_p is the number of people on platform, including passengers and staff, and c is the passing capacity of the staircase/escalator.

4.3.4. Time for Arriving at Safe Spots.

$$t_4 = \frac{L_p}{v}, \tag{7}$$

where L_p is the length of the passage from the escalators/stairs to the safe spot.

4.3.5. Nonuniform Passage Deviation Time. People may gather in one passage during evacuation. Due to the distance between passages, an unbalanced gathering in the passages may delay the progress of evacuation. The maximum time deviation caused by an unbalanced gathering can be determined by

$$t_5 = \frac{L_d}{v}, \tag{8}$$

where L_d is the distance between two different passages [11].

The total evacuation time is therefore given by

$$t = t_1 + t_2 + t_3 + t_4 + t_5. \tag{9}$$

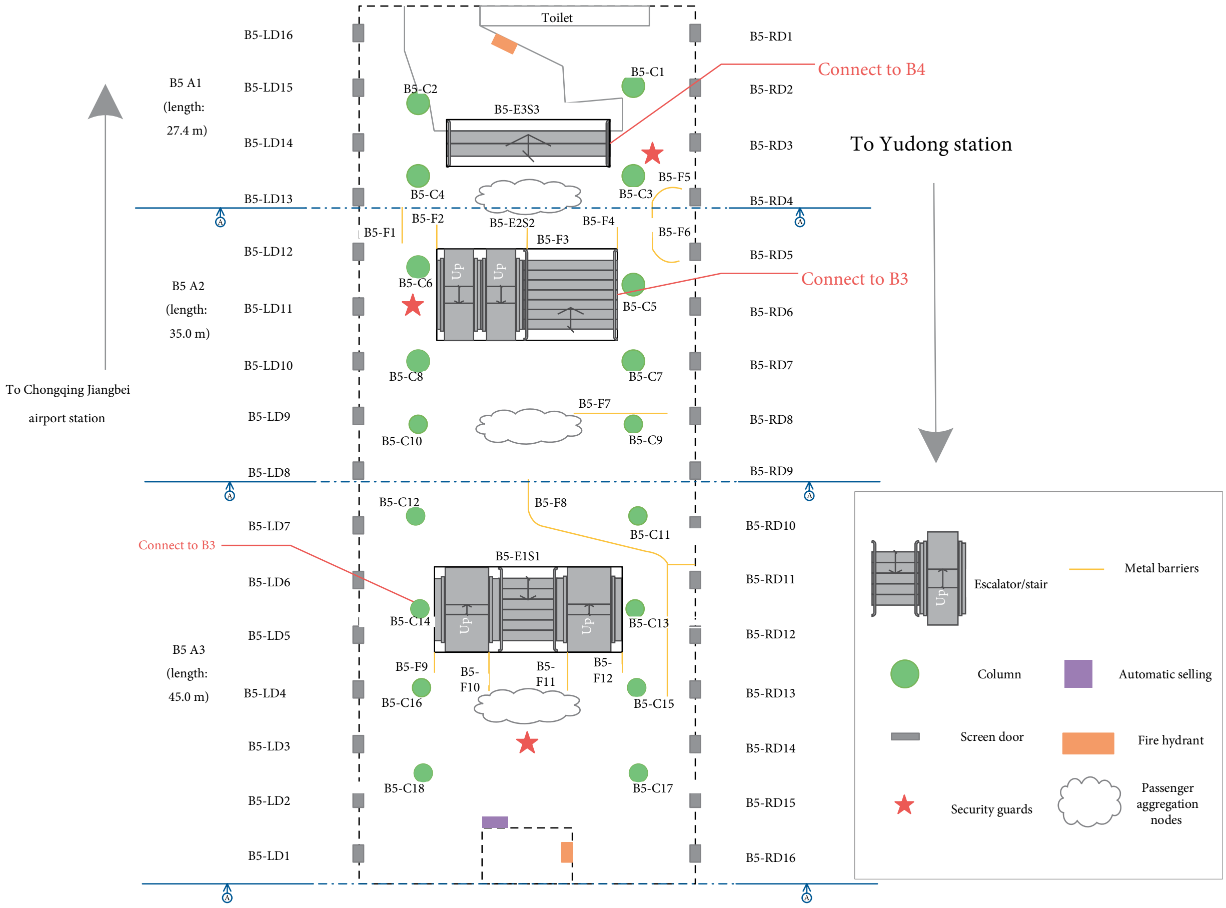

FIGURE 2: Layout of B5 floor (source: plotted by authors).

4.4. Walking Speed. Pedestrian walking speed has been explored in many studies. Normally free walking speed can be regarded between 1.2 m/s and 1.8 m/s [51]; an experiment by the National Traffic Safety and Environment Laboratory (Tokyo) of 28 persons walking on a crosswalk obtained an average walking speed of 1.2 m/s; while Imanaka and Yasui (2003) investigated 1444 pedestrian walking speeds on a crosswalk in front of a railway station during commuting hours and reported the average walking speed to be 1.7 m/s [52]. The comfortable walking speed ranged from 1.27 m/s (for women in their seventies) to 1.46 m/s (for men in their forties), while the maximum walking speed range from 1.74 m/s (for women in their seventies) and 2.53 m/s (for men in their forties) [53]. The walking speeds of pedestrians at the time of accidents are higher than on a crosswalk. Matsui et al. (2013) obtained the average pedestrian walking speed of 2.0 m/s through the investigation for 101 near-miss accidents [54]. According to the above studies and experiments, the passengers walking speed is determined as 2.0 m/s in this study.

5. Results

5.1. Coding of Facility Nodes. The detailed field investigation indicated screen doors, escalators/stairs, metal barriers, and columns are passenger aggregation nodes and coded by their first capital letter. For example, the screen doors in the left side of the B5 floor were coded as B5-LD1, B5-LD2..., and the escalators/stairs, metal barriers, and columns in B5 floor were coded as B5-ExxSxx, B5-Fxx, and B5-Cxx, respectively. Moreover, each floor in the CRTSs was classified into three areas according to the length data. The areas were coded as BX AX. The layout plan for B5, for example, is shown in Figure 2.

5.2. Emergency Evacuation Routes in Different Risk Scenarios. The simulation of the emergency evacuation was conducted for an accident occurring in a stationary train on B5 floor, as evacuation routes in this scenario are the longest. The different locations of accidents, including areas A1, A2, and A3, lead to different evacuation routes. The evacuation routes may go through screen doors, passages, metal barriers, escalators/stairs, and turnstiles, and end at the station exits. Taking the escalators/stairs as the key points, and suppose an emergency accident happens in a stationary train on B5 floor, the evacuation routes from B5 floor are shown in Table 2, and the evacuation times being calculated according to Equation (9) in Section 4.3.

5.3. Emergency Evacuation Simulation. Through field investigation, the number of passenger agents reaches to the maximal level when train arrives. In this condition, the average passenger number of every screen door is around 40.

Table 2: Emergency evacuation routes and evacuation time.

No.	Accident occurring area	Evacuation routes	Evacuation time $t_1 + t_2 + t_3 + t_4 + t_5$
1	B5 A1	B5 E3S3 → B4 E1S1 → B4 E2S2 → B3 E2S2 → Exit7	270.6 s
2	B5 A1	B5 E3S3 → B4 E1S1 → B4 E3S3 → B3 E1S1 → Exit5	276.3 s
3	B5 A1	B5 E2S2 → B3 E3S3 → Exit5	256.2 s
4	B5 A1	B5 E1S1 → B3 E4S4 → Exit7	243.2 s
5	B5 A1	B5 E1S1 → B3 E4S4 → B3 E5S5 → B2 E1S1 → Exit1-4	293.5 s
6	B5 A2	B5 E3S3 → B4 E1S1 → B4 E2S2 → B3 E2S2 → Exit7	288.5 s
7	B5 A2	B5 E3S3 → B4 E1S1 → B4 E3S3 → B3 E1S1 → Exit5	**299.3 s**
8	B5 A2	B5 E2S2 → B3 E3S3 → Exit5	263.3 s
9	B5 A2	B5 E1S1 → B3 E4S4 → Exit7	232.2 s
10	B5 A2	B5 E1S1 → B3 E4S4 → B2 E1S1 → Exit1-4	270.6 s
11	B5 A3	B5 E1S1 → B3 E4S4 → Exit7	218.0 s
12	B5 A3	B5 E1S1 → B3 E4S4 → B2 E1S1 — Exit1-4	256.3 s

The bold value (299.3 s) is the calculated maximum evacuation time.

In daily operation, the two types of train are 6-marshalling and 8-marshalling, and only one side of the screen doors are open. Thus, generally, $6 * 40 = 240$ or $8 * 40 = 320$ passenger agents will enter the B5 floor when the train arrives. In the simulation, the maximal utilization of all the screen doors in both sides is considered, with the initial number of passenger agents on the B5 floor is determined as $2 * 320 = 640$.

In the simulation, the evacuation routes are the 12 routes in Table 2, which have been input in the AnyLogic simulation platform and the social force model has been used. The number of people going through every route is not determined, which is related with the accessibility of different route in the simulation.

Table 2 shows that the calculated maximum evacuation time is 299.3 s through the 7th evacuation route, while the minimum evacuation time is 218.0 s through the 11th evacuation route. The total simulation process lasts 308 s, which is longer than that along the routes listed in Table 2, that because the simulation time is the comprehensive evacuation

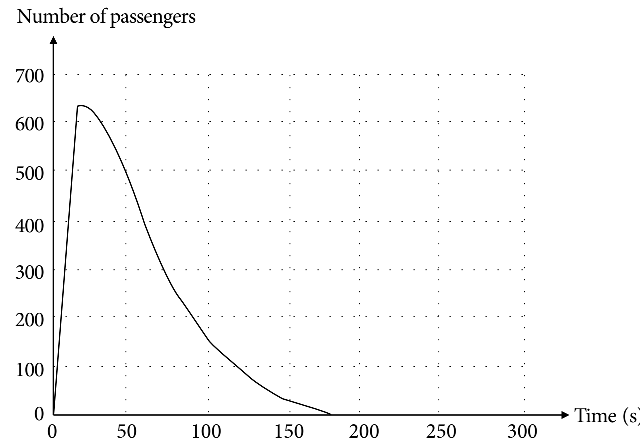

Figure 3: Relationship between passengers on B5 floor and evacuation time.

time for people evacuating through the whole 12 routes from B5 floor, and includes not only the moving time, but also the evacuees' waiting time in front of escalators, stairs, and turnstiles. The emergency evacuation time (308 s) could meet the "6 min" requirement of the Chinese Code for Safe Evacuation Design of Metro Station. It also indicates that the proposed evacuation routes are acceptable.

The relationships between the number of people on the B5 floor and evacuation time is presented in Figure 3. It shows that at the 20^{th} second, people all evacuate from the train to the B5 floor. And at about 170^{th} second, people all evacuated out of the B5 floor.

5.3.1. Identification of Distinctive Time Points. The distinctive time points during evacuation simulation were determined based on two serious problems, which are serious congestion and evacuation direction confusion. For serious congestion, some facilities, due to the width and number, would gather large numbers of people and shape as bottleneck in evacuation, such as escalators/stairs and turnstiles. Accordingly, the 28^{th} second and 58^{th} second are determined as distinctive time points. In addition, from the platform floor to the concourse floor, people go from a constrained space to a wide space and would be confused with suitable directions to safe areas. Therefore, the 170^{th} second is determined as the third distinctive time points. The simulation snapshots are shown in Figure 4.

(1) Simulation at the 28^{th} second. When an emergency accident happens on the B5 floor, the passenger agents go through escalator/stair to escape to the safety areas. At the 28^{th} second, the 640 passenger agents gather at the entrances to the escalators/stairs in B5 floor—B5 E1S1, B5 E2S2, and B5 E3S3 - which encounter serious congestion in the shape of an arch, especially around B5 E1S1 and B5 E2S2, as highlighted in yellow circles in Figure 4. According to statistics, totally 200, 168, and 33 people around the B5 E1S1, B5 E2S2, and B5 E3S3 at the 28^{th} second, and the average number of people in per square meter of these three points is 2.581, 2.224, and 0.85. The crowd of people may further cause a stampede or other risk events. The escalators/stairs are therefore key facilities in

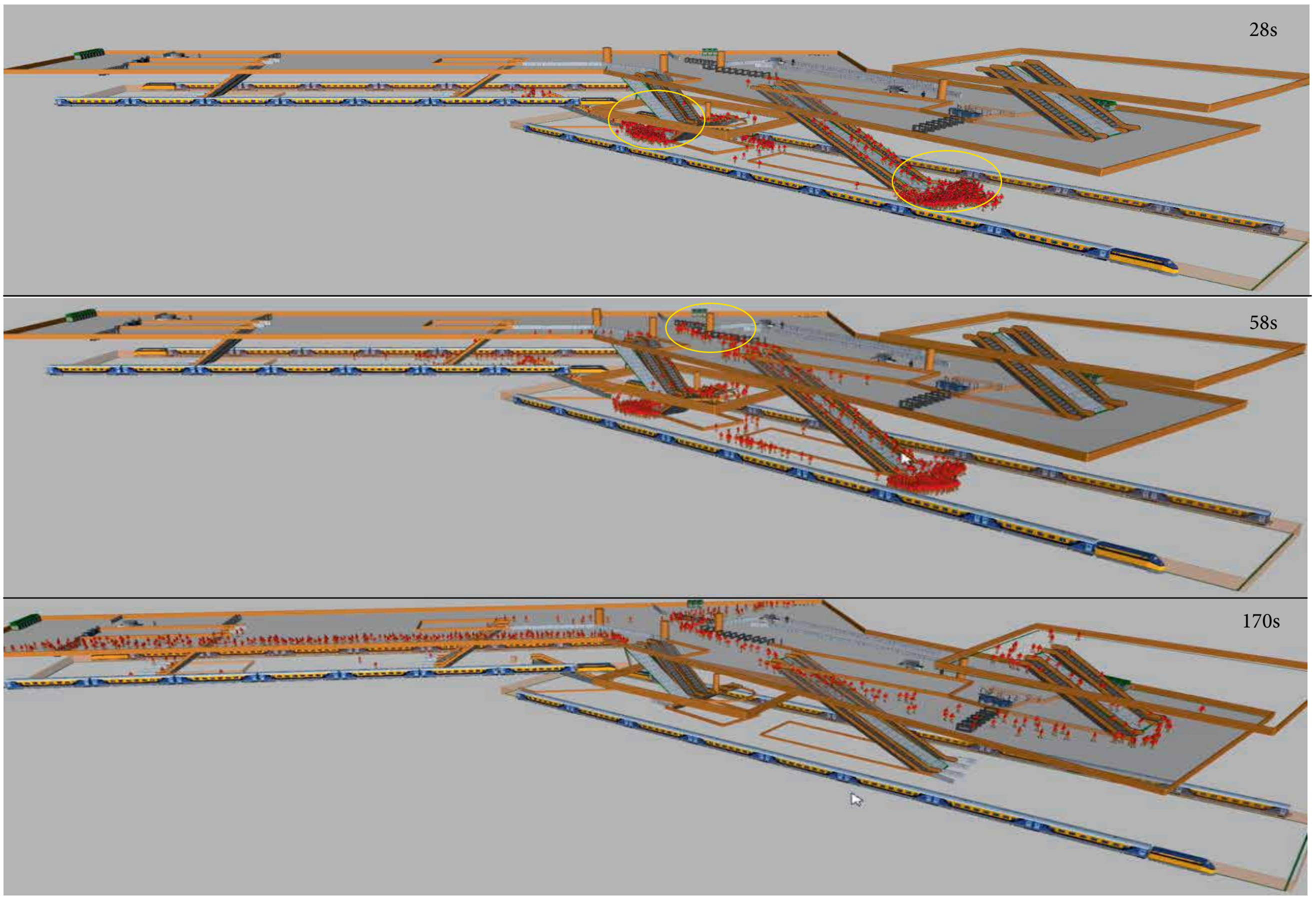

Figure 4: Emergency evacuation at the 28th, 58th, and 170th seconds.

the evacuation, as the evacuation capacity is directly related to the length and width.

(2) Simulation at the 58th second. At the 58th second, the first person (in yellow circle) is evacuated to the safe area through Exit 7 on B3 floor, as shown in the simulation scenario in Figure 4. The station is in a state of emergency and all the turnstiles are opened. From the B5 floor to the safety areas on B3 floor, the passenger agents go through screen doors, escalators/stairs, passages, and turnstiles. There is a large space on B3 floor and the evacuated people may start to push and stampede during evacuation. Thus, the number and width of turnstiles are major elements deciding the evacuation time.

(3) Simulation at the 170th second. As shown in Figure 4, all passenger agents have been evacuated to the concourse floors, B2 and B3, at the 170th second. Conformity psychology is a common phenomenon during the process of emergency evacuation [55], as most passenger agents tend to be reactive, cooperative, and follow the crowd with the same direction-attraction power. This may be because people do not clearly know the location or direction of the safety area. Thus, effective guidance for the evacuation, such as signs indicating the direction of the safety areas in the concourse floor, is necessary in the public space of the station.

(4) Simulation comparison to other studies. In this research, the 640 passengers in the Lianglukou Station are evacuated in 308 s. The average evacuation time is 0.48 s/person. Comparatively, (1) taking the two-floor canteen as an example, 268 people were simulated for evacuation, and the total evacuation time was 179.3 s (0.67 s/person) [56], (2) in the two-floor under-ground island station, considering evacuation in different escalator operation strategies and the movement state of persons on escalator, 554 pedestrians were evacuated between 195 s and 242 s (0.35 s/person to 0.43 s/person) [11], (3) taking a multifloor transfer metro station as the background, 2660 people were simulated for evacuation, and the total evacuation time was 750 s (0.28 s/person) [57]. Thus, compared to other simulation research, the simulation evacuation time of the Lianglukou station (0.48 s/person) is in the scope of the listed existing studies (0.28 s/person to 0.67 s/person). Thus, the evacuation simulation in this research is reasonable in this degree.

5.3.2. Analysis of Passenger Flow through Escalators/stairs. The escalators/stairs are the key passages for evacuation in the 3D space of multifloor structures, and the analysis of passenger flows through these points can provide information concerning the passage rate and passenger flow aggregation points, which is useful for offering guidance in the evacuation. There are three escalators on B5 floor, coded B5 E1, B5 E2, and B5 E3, each with an accompanying staircase correspondingly coded as B5 S1, B5 S2, and B5 S3, as shown in Figure 2. Figure 5 shows the number of agents passing through the different escalators/stairs.

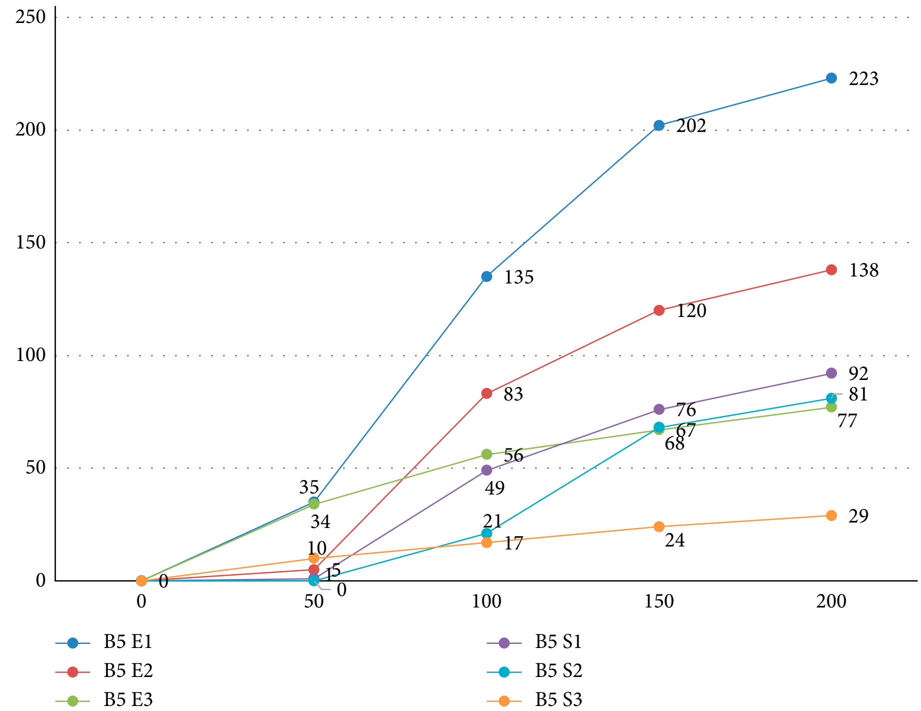

Figure 5: Number of agents passing through escalators/stairs.

As mentioned earlier, all the agents have evacuated to the concourse floor (B3) by the 170th second. According to Figure 5, the total number of agents having passed through the escalators/stairs at the 200th second is $223 + 138 + 77 + 92 + 81 + 29 = 640$. The agents evacuating from B5 E1, B5 S1, B5 E2, and B5 S2 reach the B3 floor directly, while agents evacuating from B5 E3 and B5 S3 need go further, through B4 E2 and B4 E3 to the concourse floor. B5 E1 links B5 and B3 floors directly and thus has a higher evacuation ability. Most agents choose B5 S1 to evacuate. The number of agents passing through B5 E2 ranks the second. Agents going through B5 E2 from B5 to B3 floors need an immediate transfer at the B4 floor, which causes crowded clusters and extends the evacuation time. Agents who evacuate through B5 E3 should firstly arrive at B4 floor, then to B4 E2 or B4 E3, before arriving at B3 floor. The transfer from B5 E3 to the B4 escalators takes more time. Thus, only a few agents pass through B5 E3 and B5 S3.

It can be concluded, therefore, that (1) B5 E1 and B5 E2 are key facilities for emergency evacuation, and (2) the evacuation numbers through the escalators are unbalanced due to accessibility difficulties of the evacuation routes. Based on these results, further guidance for evacuation can be formulated.

5.4. Evacuation Simulation for Nonhomogenous Agents. Accounting for different kinds of crowds, further experiments on the AnyLogic simulation platform have been conducted, that considering 20% the aged/disabled people integrate into the evacuees, respectively. The speeds of these two kinds of people are determined as 1.58 m/s and 1.41 m/s [26], respectively. The simulation results of the evacuation time are shown as Table 3. The results present that the evacuation time is longer than the simulation for the homogenous agents (308 s). These conditions should be considered in practice management.

Table 3: Evacuation time for nonhomogenous agents.

No.	Experimental agents	Evacuation time (s)
1	100% original passengers	308 s
2	20% the aged + 80% original passengers	341 s
3	20% disabled people + 80% original passengers	373 s

5.5. Optimization Measures for the Emergency Evacuation. Due to the possibility for the metal barriers to create a bottleneck during an emergency evacuation [58], the optimization strategies are mainly concerned with removing metal barriers in different places. Six experiments were conducted to compare the optimization effects. According the simulation, when an accident happens in a train on B5, the evacuation time is 308 s without optimization. The first experiment was to remove all the metal barriers in B5. The second and third experiments were to remove parts of metal barriers in B4. B4 E1S1 was included in the two experiments as it is a necessary way for people to enter B4. The fourth, fifth, and sixth experiments are to remove metal barriers in different areas of B3. The results are shown in Table 4.

This indicates that removing all the metal barriers in B3 A2 could reduce the evacuation time to the maximum degree of 48 s. The metal barriers of B3 A2 are mainly concentrated in front of B3 E2S2, which is directly linked to Exit 5. Moreover,

Table 4: Optimization results of the six experiments.

No.	Experiment	Evacuation time (s)	Reduced time (s)
1	No optimization	308	0
2	Remove all metal barriers on B5 floor	280	28
3	Remove all metal barriers on B4 E3S3 and B4 E1S1	291	17
4	Remove all metal barriers on B4 E2S2 and B4 E1S1	296	12
5	Remove all metal barriers on B3 A1	294	14
6	Remove all metal barriers on B3 A2	260	48
7	Remove all metal barriers on B3 A3	290	18

removing all the metal barriers in B5 floor is also a useful optimization strategy, as it could reduce the evacuation time by 28 s.

Removing metal barriers in the occurrence of an emergency condition requires lots of efforts of staff members. During the removing process, collisions between metal barriers and people may happen and lead to further obstacles. Thus, the implementation of removing metal barriers should consider the evolution results. Removing metal barrier exercises should be implemented regularly for effective and efficiency actions. Staff should command the removing methods.

6. Conclusion

As a main component of modern transportation, rail transit is highly popular in many Chinese cities. Rail transit stations with a multifloor structure integrated in 3D space have become greatly populated spaces. The passenger flow volumes of many stations are reaching or even exceeding their designed long-term maximum capacity. As rail transit stations are urban public spaces, their overcrowding makes them subject to threats from various emergency accidents. Research involving emergency evacuation simulation and optimization based on their complex structure is therefore significant for the safe operation of the stations.

The main contents of this study comprise the illustration of the complex structural characteristics of CRTSs, the establishment of an emergency evacuation theoretical framework of CRTSs, an emergency evacuation simulation for the case station, and the analysis of potential emergency evacuation optimization strategies. Using Chongqing's Lianglukou rail transit station as the case study, the proposed evacuation strategies could meet the "6 min" requirement of the Chinese Code for Safe Evacuation Design of Metro Station, which provide a useful reference for the safety management of the Lianglukou station. From this case, four main simulation results were obtained:

(1) Escalators/stairs and turnstiles are key facilities in the evacuation. The evacuation capacity of the station is directly related to the length, width, and number of escalators/stairs, especially at the beginning stage of the evacuation. Besides, the number and width of turnstiles are also a main element deciding the evacuation time. These could be illustrated by the evacuation situation in the Lianglukou station at the 28th and the 58th seconds.

(2) Effective guidance for the evacuation is necessary in the public space of the station. The importance of effective guidance could be resulted from the evacuation phenomenon in the Lianglukou station at the 170th second. Effective guidance in the emergency evacuation includes signs indicating the direction of the safety areas, voice broadcast, evacuation commands from professional staffs or policemen, etc., which change dynamically according to the situation and aims to tell people the location or direction of the safety area [59]. Effective crowd guidance can improve egress efficiency, occupant survivability, and mitigate or prevent undesirable consequences such as stampeding or blocking [60].

(3) Passenger aggregation nodes should be guided for balanced evacuation. Passenger aggregation nodes should be found through simulation experiment. In the Lianglukou station, the B5 E1 and B5 E2 are key facilities and passenger aggregation nodes for the emergency evacuation of the station, and guidance should be developed to balance the number of evacuees using each escalator/stair.

(4) Removing metal barriers is a useful measure to optimize evacuation time. Removing metal barriers would be a useful strategy to shorten evacuation time, but the implementation should be exercised regularly in daily operation.

For the proposed emergency evacuation research methods, the AnyLogic simulation platform and the social force model could also be used in emergency evacuation for some other CRTSs, such as railway station, commercial complex, airport terminal, etc. In addition, for the established emergency evacuation framework, the four aspects of the framework could be adopted through combining with the characteristics of the research CRTSs. Firstly, the emergency accidents could be determined according to the statistics of accidents of the research CRTSs. Secondly, the accident spots and evacuation routes should be analyzed based on the structure of the research CRTSs and some scenarios should be considered. Thirdly, the evacuation time calculation method could also be used in evacuation time calculation for some other CRTSs. Fourthly, the review for the walking speed studies and the consideration for the walking speed could also be adopted in other studies. Thus, though the established framework could not be used in the emergency evacuation research for other CRTSs directly, the framework provides meaningful and useful references. The proposed simulation method is helpful for other CRTSs to determine reasonable emergency evacuation strategies according to the evacuation process and the structure/passenger characteristics of the case, which promote the safe operation of the urban rail transport system. Besides, the research could also supply valuable emergency evacuation guidance for passengers.

In the future research, three aspects will be mainly focused to further improve the simulation, including (1) collecting the real-world data and compare to the model output, (2) adding the subjective factors, such as psychological factors and cognitive factors, to the evacuation methodology, and (3) considering more emergency simulation scenarios, such as bottleneck in safety exits or passageways.

Data Availability

The data used to support the findings of this study are available from the field investigation upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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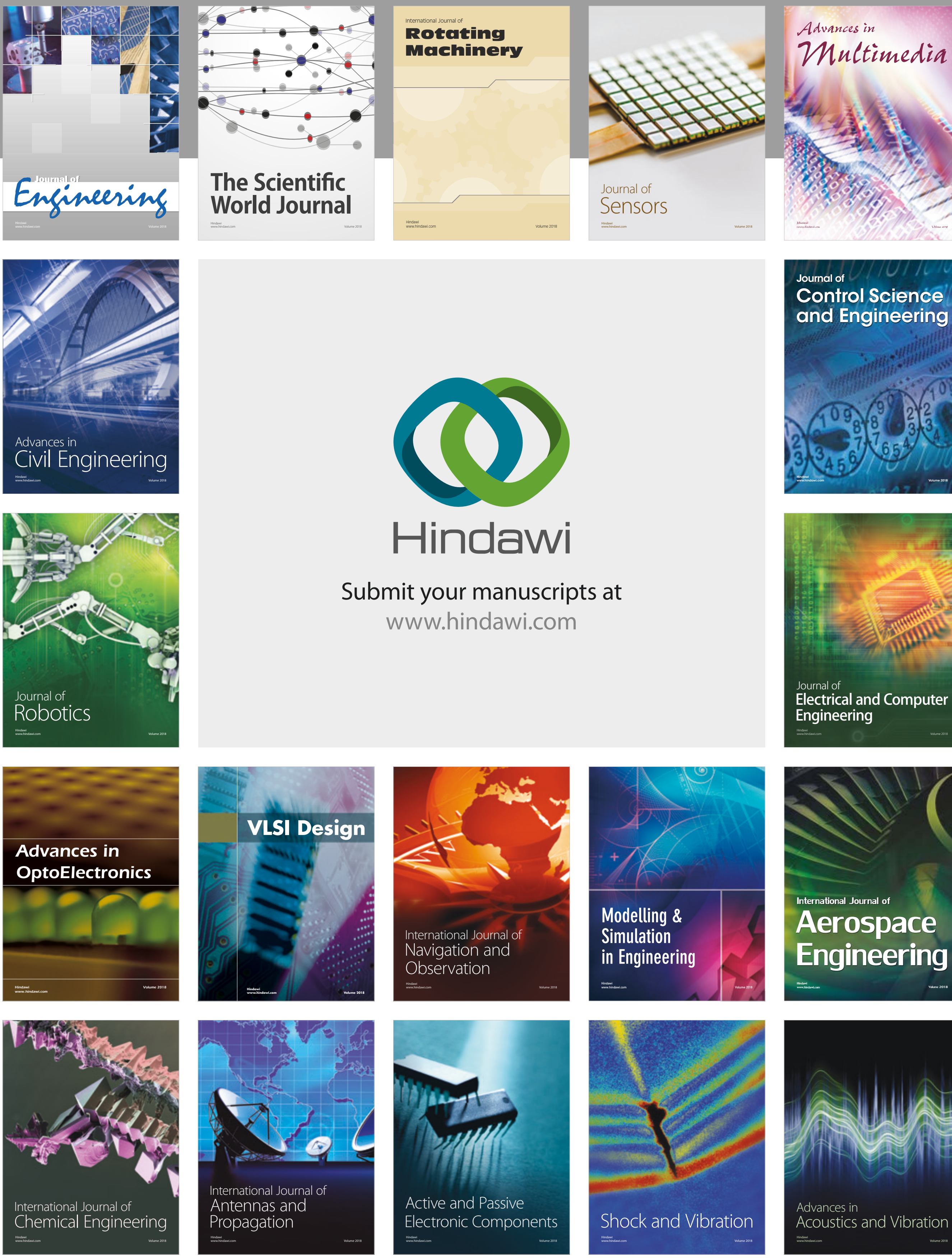

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