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Research Article

Fire Evacuation Process Using Both Elevators and Staircases for Aging People: Simulation Case Study on Personnel Distribution in High-Rise Nursing Home

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There were increasing concerns on the possibility and suitability of using elevators for high-rise building evacuation because, through the improvement of the elevator system, the self-evacuation ability of age people is promoted as much as possible in the process of an emergency evacuation. The combined evacuation using both elevators and stairs was put into discussion. However, there was no empirical evidence and numerical simulation on emergency evacuation using both elevators and staircases for aging people in high-rise nursing homes. Therefore, using one case study, this paper simulated the emergency evacuation in a high-rise nursing home using variables such as the distribution of the elderly with different physical conditions, the proportion of the elderly in different physical conditions, the number of the elderly, the number of floors, the number of elevators used, and the priority of the elevator floor. By simulating the evacuation process in various scenarios, the general distribution strategy of high-rise nursing home and the optimal use of the elevator-stair combination during the emergency evacuation were developed. Results show that the elevator-stair combination of evacuation is more effective than using elevators or stairs alone. Increasing the number and speed of elevators can reduce evacuation time. Categorizing elderly people on each floor according to their physical conditions could reduce the evacuation time than randomly distributing them.

1. Introduction

With the advancement of science and medical technology, human beings are living longer and the world is facing the major challenge of an aging population [1–3]. Population aging has been seen in many nations [4], and most elderly people choose to live in nursing homes or hospitals during the last years of their lives [5]. More high-rise nursing homes have been built in cities to meet the needs of an aging society, but the evacuation of the elderly has become a serious problem in emergencies [6]. To reduce casualties and property losses in unexpected situations, an effective evacuation plan should be adopted [7]. Older people entering nursing homes are often seriously ill [8, 9], many of them need regular contact with the health care system to stay alive and function [10]. Those standard evacuation procedures are therefore not well suited for these vulnerable populations [11]. Aging people not only need the help of others to evacuate safely but also hinder the evacuation of others [12]. Due to mobility problems, evacuation from the stairwell is extremely difficult for aging people [13]. Therefore, since the World Trade Center attack on September 11, there were increasing concerns about the possibility and suitability of using elevators for high-rise building evacuation [14]. Through the improvement of the elevator system, the self-evacuation ability of age people is promoted as much as possible in the process of emergency evacuation [15]. The combined evacuation using both elevators and stairs was significantly improved [16]. Computer simulation can create dynamic building information to observe the behavior of structures or people, and the design of the built environment can be promoted to respond to emergencies [17]. Agent-based evacuation simulation could simulate individual movements in high-rise building evacuation [18]. An evacuation simulation of a 40-story building found a refuge layer in the middle which could allow more people to evacuate [19]. When evacuating different age groups, crowded elderly people on the stairs were evacuated by the elevator, which effectively accelerated the evacuation [20]. A study regarding the impact of staircase design on building plane evacuation found that the evacuation time and many parameters were linearly associated [21]. However, there was no empirical evidence and numerical simulation on emergency evacuation using both elevators and staircases for aging people in high-rise nursing homes. Therefore, this study simulated the emergency evacuation in high-rise nursing homes using variables such as the use of the elevator, the distribution of the elderly with different physical conditions, the proportion of the elderly in different physical conditions, the number of the elderly, the number of floors, the number of elevators used, and the priority of the elevator floor.

2. Review Nursing Home Evacuation

Evaluating building evacuation performance design in an emergency is complex, requiring simulation tools for analysis and a large amount of manual input [22]. Built environment and evacuation behavior are decisive factors in establishing evacuation performance [23]. The built environment includes the distance from the exit, the width of the passage, the degree of congestion, and the capacity of the exit, which affect the route choices of pedestrians [24]. Human factors in evacuation include body, cognition, motivation, and social variables [25], and psychological factors affect people's behavior and panic in the case of evacuation, which makes the density of pedestrians larger and the distance between them smaller [26]. The knowledge of fire safety and emergency preparedness before an emergency has an important impact on fire response performance and evacuation response time [27, 28]. The clustering of evacuated personnel could slow down the average speed of evacuation [29]. The familiarity of the personnel with the site will greatly reduce the evacuation time, but excessive conservative or impulsive evacuation will lead to an increase in evacuation time. A small number of leaders in the pedestrian can significantly reduce evacuation time [25].

In recent years, efforts by researchers studied many high-rise buildings' evacuated simulation models. The pre-evacuation behavior was investigated using the Support Vector Machine (SVM) method in Hong Kong, and the escape route planning, safety education, equipment maintenance, and fire safety management based on BIM model buildings were established [30]. Simulation can be used to calculate the required safety exit time and available safety exit time to assess the ability to evacuate in the event of fire [31]. Applying evacuation regulations to establish a BIM-based automation system, designers and owners can check whether BIM data meets evacuation regulations, which is critical for disaster prevention systems and exit routes for tall and complex buildings [22]. The risk and route conditions were detected by a route selection model based on human organs and features, the degree of congestion of the route is determined, and the evacuation route is selected according to the personal characteristics of each occupant [32]. A stratified route planning algorithm was used to find the best evacuation path to quickly guide the evacuees to the exit [33]. A cellular automaton crowd route choice model could simulate the evacuation process of large indoor spaces in various environments [34]. When fire or chemical leak in the event of an emergency evacuation process linear programming model is viable [35], a cellular automata (CA) model was developed to describe pedestrian movement in the presence of collision avoidance during the evacuation, showing that more collision avoidance behavior hurt evacuation efficiency, but more competitive behavior had no significant positive impact on evacuation efficiency [36]. A pedestrian evacuation system for large buildings was to monitor pedestrian flows in complex facilities to assist decision makers and security agencies in emergencies [37].

The state of panic in an emergency can increase the evacuation time of people, especially elderly people and people with disabilities who are in poor health. The mental disability caused by the identification of unexpected risks in special populations has increased the average evacuation time [35]. Older people who are over 65 years old doubled the risk of dying in a fire compared to the general population [38]. Most of the elderly, living in nursing homes, need to use crutches, wheelchairs, or other occupants or firefighters to evacuate, and only a small number of elderly people can evacuate without help [39]. When these special groups are evacuated in high-rise buildings, large-scale and slow-moving elderly people such as those in wheelchairs and using a stretcher tend to block the channel, with serious ramifications for other passengers to evacuate [40–42].

Due to the special nature of high-rise building evacuation, the International Building Code allows the use of occupant evacuation elevators as a third staircase to facilitate the safe evacuation of high-rise building personnel [43]. As a result, high-rise buildings are equipped with elevator evacuation that can be used for the elderly and disabled in unexpected situations [44–46]. There is an upper limit to the optimization process of elevator-assisted evacuation [47]. The elevator evacuation time is determined by influencing factors such as the number of elevator evacuation, evacuation floor height, elevator speed and acceleration, elevator capacity, and elevator door width [28]. The spacing design of the evacuation floor is directly related to the characteristics of the elevator and the occupants of the building. The evacuation process can be optimized while the appropriate proportion of building occupants are transported to the ground by elevators while others are evacuated by stairs [24]. Using elevators to move all passengers to the ground safety point is not the best solution [29]. People who use stairs or elevators to evacuate are mainly affected by the floor. In an emergency, the waiting time of the passengers and the proportion of waiting people are affected by the height of the floor, and it is unreasonable to wait for the elevator indefinitely [48]. Even if people choose elevator evacuation, they may not wait if it takes a long time to reach [49]. Stair evacuation plays a vital role in building evacuation, as the evacuation time can be predicted by a simulation model and architects can develop evacuation plans and strategies based on simulation results [50]. The consolidation behavior of stairwells could reduce the speed of pedestrian flow. The stairs are the major exporters of high-rise buildings [51, 52]. As the population grows, the impact of obstruction caused by people with disabilities on evacuation time becomes more apparent [53, 54].

3. Research Methods and Procedures

The basic model used in this simulation was a 17-story nursing home for aging people located in Fujian, China. Figure 1 shows the layout of the first and third floors of the nursing home in Pathfinder simulation software. It is 72 m long, 15 m wide, and 61.6 m high. The first floor is the lobby office area, and the second floor includes the chess room, the dining hall, and the activity room. The third floor is the residential area for the elderly. The first floor has a height at 4 m and the 2nd to 17th floors have a height of 3.6 m each. Each floor has 56 beds, and the 4th to 17th floors were designed as same as the third floor. The building has three exits, two stairs with a tread of 0.3 m and a riser height of 0.15 m, and two elevators with a length of 3.6 m and a width of 2.7 m. The following is the setting of elevator parameters in Pathfinder simulation software. The elevator load was calculated according to the software according to the size of the personnel and the size of the elevator in STEERING mode. The nominal load of the two elevators in this model was 29 people. The open and close time of the elevator doors was calculated by 7 s, and the acceleration of the elevator was $1.2\,\mathrm{m/s^2}$. The elevator bounds were from the 1st floor to the 17th floor, and the first floor was the discharge layer of the personnel. In the event of an emergency, the person connected to the elevator on the floor should be sent directly to the first floor for evacuation. In this process, even if the elevator did not reach the nominal load, it would not pick up more people on other floors. The modeling of types of people living in this nursing home was complicated. According to the physical conditions of the elderly, the elderly people could be divided into the no-aid elderly people (NAEP) and elderly people who use auxiliary tools. Old people who use assistive tools were divided into the elderly people who use single-crutch (SCEP), the elderly people who use double-crutches (DCEP), the elderly people who use a manual wheelchair (MWEP), the elderly people who use power wheelchair (PWEP), and the elderly people who use Evac + Chair (ECEP). Evac + Chair evacuate the elderly with a poor physical condition, which is 50% faster than other devices, so the elderly using stretchers choose to use Evac + Chair for evacuation. The formula for calculating the total evacuation time of personnel is as follows:

$$T = T_0 + T_1, \quad (1)$$

where T is the total evacuation time, T_0 is the evacuation exercise time, and T_1 is the evacuation delay time. The parameter setting and evacuation delay time in the simulation were set manually. Tables 1 and 2 show the parameter values of different types of elderly people in Pathfinder software settings. According to the experimental investigations [55–61], the movement speed, the width of the occupation, the separation distance from other people, and the delay time of evacuation were obtained in Table 1. For example, Speed of Nurse in the software is 1.549 m/s, Shoulder Width is 40 cm, Comfort Distance is 0.08 m, and Delay Time is 0.8 s. The speed of NAEP in the software is 1.274 m/s, Shoulder Width is 40 cm, Comfort Distance is 0.08 m, and Delay Time is 0.8 s. Similarly, parameter values of other types of elderly people can be set. The width of the occupation is the projection width of the elderly on the ground when they are stationary. For example, the width of the occupation of a standing elderly person is shoulder width, and the width of the occupation of an elderly person in a wheelchair is the width of a wheelchair. The comfortable distance is the distance that people habitually maintain with each other. Within this distance, personnel can switch directions freely and avoid collisions. They must also follow each other and use space reasonably. For example, the auxiliary tools used by MWEP, PWEP, and ECEP have a large width, and any movement or rotation requires a large space. To ensure normal movement and avoid collisions, the required comfort distance is large. When an emergency occurs, the distance between the elderly will be less than the comfortable distance, and even events such as crowding and stamping will occur. Therefore, the comfort distance of different types of elderly in the emergency simulated in this paper is the minimum distance kept between people, which is 0.08 m. The delay time is the difference between when an emergency occurs and when people evacuate. The delay time for a self-evacuated person is the person's reaction time. It is known from the literature that the average human response time is 0.8 s. ECEP needs to wait for the help of others before the evacuation, so the delay time of ECEP is the time to assist people to reach their location. The speed of the upstairs and the horizontal movement speed of the assisting staff

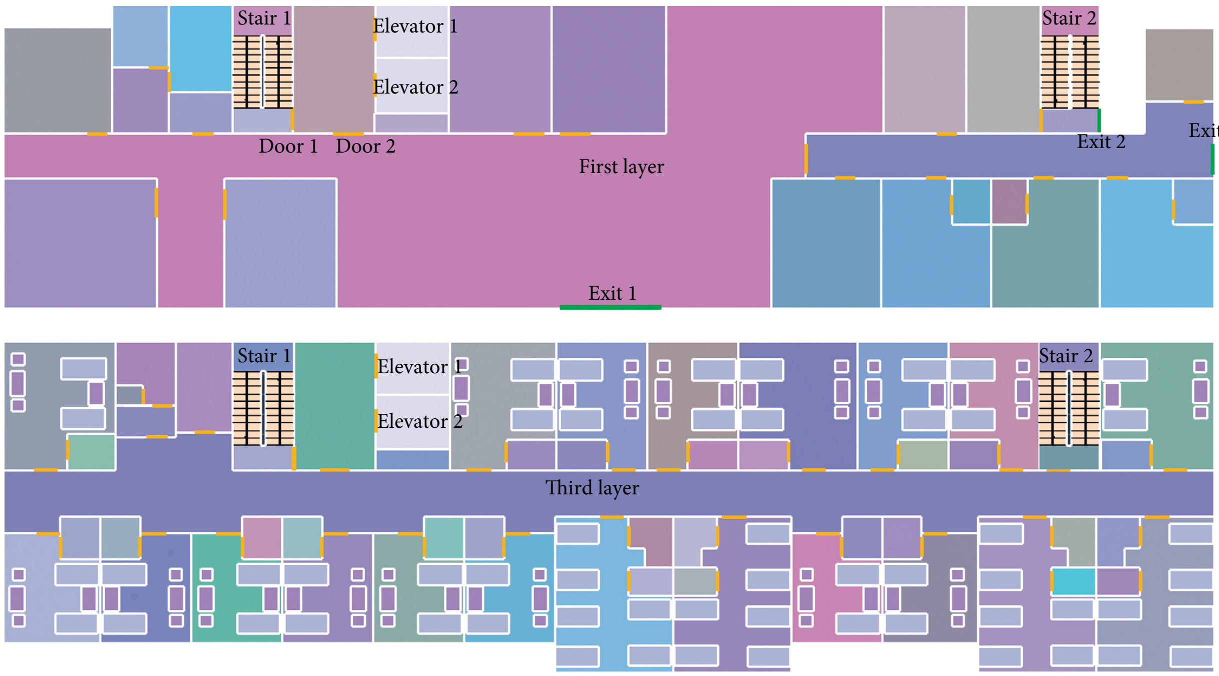


Figure 1: Floor plan of a high-rise nursing home for aging people.

Table 1: Attributes of the elderly with different physical conditions.

Types	Moving speed (m/s)		Occupied width (m)	Comfort distance (m)	Delay (s)
	Horizontal	Stair-ascending			
Nurse	1.549	1.146	0.4	0.08	0.8
NAEP	1.274	0.85	0.4	0.08	0.8
SCEP	0.873	0.433	0.45	0.13	0.8
DCEP	0.779	0.332	0.5	0.18	0.8
MWEP	0.64	0	0.98	0.87	0.8
PWEP	0.7	0	0.98	0.87	0.8
ECEP	1.5	0.81	1.1	1.2	See Table 2

Table 2: Delay time for elderly people using ECEP on different floors.

Floors	Delay time (s)	Floors	Delay time (s)
2	14.73	10	46.06
3	18.64	11	49.98
4	22.56	12	53.90
5	26.48	13	57.82
6	30.39	14	61.73
7	34.31	15	65.65
8	38.23	16	69.57
9	42.15	17	73.49

were available according to the survey value and the time formula for assisting personnel to reach the floor is as follows:

$$T_3 = \frac{H}{V_0} + \frac{L}{V_1}, \quad (2)$$

where T_3 is the time to assist the person to reach the floor of the old men, H is the height of the floor where the old men were located, L is the horizontal distance of an old man's position from the stairs, V_0 is the speed to assist the staff to go upstairs, and V_1 is the horizontal speed of the assisting personnel. Delay time for elderly people using ECEP on different floors is listed in Table 2.

4. Data Interpretation and Analysis

4.1. Simulation Using Elevator Evacuation. Most of the elderly people living in nursing homes were unable to take care of themselves. Old people with poor physical condition need the help of the medical staff and daily care, so it is necessary to arrange nursing staff for the floor where the elderly who are in poor health live. The number of elderly people in the nursing home in Pathfinder software was set in Table 3. In the event of an emergency, elderly people in wheelchairs need to replace the evacuated aids with crutches if they need to evacuate through the stairs. Table 4 shows five different scenarios in Pathfinder software simulation, including (i) all elevators, (ii) all stairs, (iii) one elevator + two stairs, (iv) two elevators + two stairs, and (v) when the maximum speed of the elevator increased. The elderly in the nursing home were randomly distributed according to the proportion of the people in Table 3. The priority of the

Table 3: Number and distribution of the elderly using different auxiliary tools.

Items	Nurse	NAEP	SCEP	DCEP	MWEP	PWEP	ECEP	Total
Occupants	24	56	112	108	108	108	324	840
Proportion (%)	2.86	6.67	13.33	12.86	12.86	12.86	38.57	100.00

Table 4: The description of Scenarios A1–A5.

Scenario	Description
A1	All the elderly are evacuated by elevator; the elevator speed is 2.5 m/s
A2	All the elderly use stairs to evacuate
A3	All the elderly are evacuated by an elevator + two stairs; the elevator speed is 2.5 m/s
A4	All the elderly are evacuated by two elevators + two stairs; the elevator speed is 2.5 m/s
A5	All the elderly are evacuated by two elevators + two stairs; the elevator speed is 5 m/s

elevator was from the upper to the lower floors. To eliminate the chance factor, each case was simulated 10 times. Table 5 recorded the occupant evacuation time of ten simulations in Scenarios A1–A5.

The evacuation time using only elevators and only stairs reached the maximum. The evacuation time using only elevators and only stairs were 52% and 30%, respectively, higher than using both elevators and stairs. The combination of using both the stairs and elevators could shorten the evacuation time. The percentage of evacuation time that no elevator has increased over one elevator was (2778–2354)/2778 = 15.3%. The percentage of evacuation time increased using one elevator compared to that using two elevators was (2354–2131)/2354 = 9.5%. From Scenario A4 and Scenario A5, the speed of the elevator also played an impact on the evacuation time, and the percentage of evacuation time reduction when the speed of the elevator increased from 2.5 m/s to 5 m/s was calculated as (2131−1809)/2131 = 15.1%. Increasing the speed and number of elevators resulted in a significant reduction in evacuation time. When elevators stairs were used for evacuation, the increased number of elevators did not increase the elevation speed; thus, in the case of an emergency evacuation, the elevator speed should be expedited.

Different floors and different types of seniors have different delay times. The delay time values are shown in Tables 1 and 2. In pathfinder simulation software, adding "Wait" in "Behavior" means that the delay time for older people is different. Although the use of a combination of elevators and stairs to evacuate and increase the speed of the elevator can speed up the evacuation efficiency, the random distribution of different types of elderly in the building has caused a large congestion phenomenon. For example, ECEP is randomly distributed on each floor, and the ECEP on the top floor waits for people to assist for a long time. Figure 2 is a graph showing the cumulative number of evacuations per door over time in Scenario A5. The time for completing the evacuation of stairs 1, stairs 2, and elevators are quite different. The vast majority of elderly people use elevators to evacuate, and the stairs cannot perform the evacuation function, extending the overall evacuation time.

4.2. Influence of Different Types of Personnel Distribution on Evacuation Time. The distribution of the elderly with different physical conditions could have an influence on evacuation time, and the scene descriptions of three different distributions of the elderly in Pathfinder software were listed in Table 6. Combining elevators and stairs and increasing the maximum speed of the elevator could reduce the evacuation time; thus, the following simulation adopted the evacuation mode of elevator stairs combination, and the maximum running speed of the elevator was 5 m/s. Table 7 shows the number of distribution of personnel on each floor in Scenario B2 in Pathfinder software. There numbers 4-5 in Table 7 represent the number of elderly people from the fourth floor to the fifth floor, and the number of elderly people living on the fourth floor and the fifth floor was 56. Table 8 shows the distribution of personnel on each floor in Scenario B3 in Pathfinder software. The proportion of each type of old people in Scenarios B1, B2, and B3 was the same, and the distribution of the area in which the elderly people were staying was different. All the elderly people randomly chose the evacuation methods, and the priority of the elevator was from the upper to the lower.

According to the different personnel distributions in Scenarios B1, B2, and B3, 10 simulations were performed, respectively, and the simulation results were shown in Figure 3.

Scenario B1 used a longer evacuation time than Scenario B2 because different types of elderly people were randomly assigned to each floor, and elderly people with poor physical condition could easily cause congestion on the stairs during evacuation through stairs. If the ECEP was on the middle floor, when the assisting person arrived at the target floor to help evacuate, the person on the upper floor was evacuated to that floor. If ECEP chose the stairs to evacuate at this time, the space occupied by the evacuation was the largest, and the faster moving speed of the assisting personnel could not function, so the evacuation efficiency was very low. When this happened, not only the ECEP wads are congested in the stairs but also the old people who used crutches or even self-care could not reach the bottom layer due to the blockage of the stairs, so the evacuation time was the longest. The ECEP was uniformly arranged on the top layer. When the assisting personnel reached the top level to assist the ECEP

Table 5: Occupant evacuation time of ten simulations in Scenarios A1–A5 (unit: s).

Scenario	1	2	3	4	5	6	7	8	9	10	Mean	Percent
A1	3209	3260	3098	3367	3298	3198	3321	3048	3306	3386	3249	52
A2	2725	2743	2681	2801	2825	2722	2941	2595	2856	2895	2778	30
A3	2306	2340	2302	2384	2360	2306	2503	2165	2406	2463	2354	10
A4	2091	2160	2013	2201	2156	2101	2305	1864	2150	2264	2131	0
A5	1780	1670	1722	1826	1876	1798	1984	1657	1874	1905	1809	−15

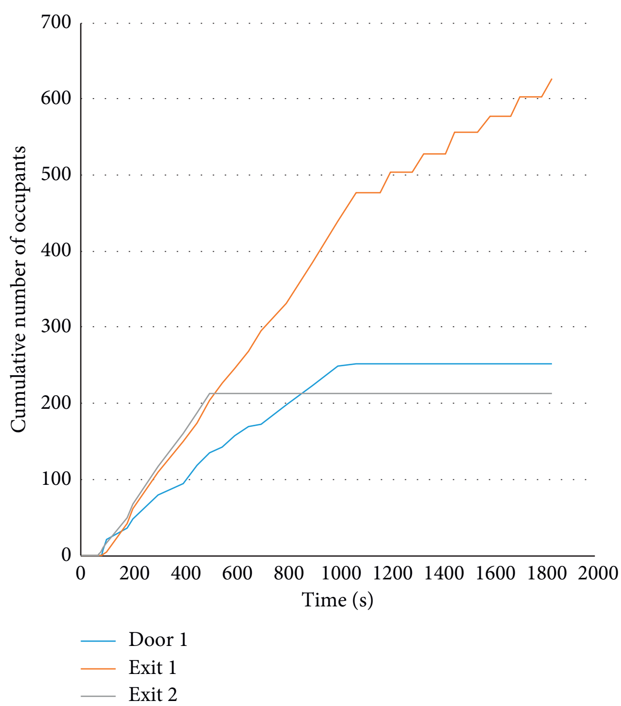


Figure 2: The cumulative number of evacuations per door over time in Scenario A5.

evacuation, the underlying NAEP was evacuated in an orderly manner, and the evacuation efficiency was improved. The evacuation time of Scenario B3 was smaller than that of Scenario B2 because the time required to assist the person to reach the bottom layer was shorter. Although ECEP occupied a large area when evacuated, the evacuation rate was faster than other elderly people. When the assisting personnel reached the ground floor, they could quickly evacuate through the stairs. Meanwhile, the seniors of the upper level did not reach the lower level yet, and the old people could be evacuated through the stairs as quickly and orderly as possible. When the old man who evacuated through the stairs reached the lower level, the lowest number of layers of the ECEP evacuated through the stairs was evacuated, so the congestion was not serious. The ECEP of the top floor in Scenario B2, no matter being evacuated by stairs or elevator, needed assistance from personnel to reach the stairs or elevators. It took longer for the personnel to reach the top floor thus the ECEP delay time was longer. The reverse movement of assisting personnel and evacuated old people in the stairwell affected the overall evacuation efficiency, making the stairs congested and prolonging the evacuation time. The evacuation time of Scenario B2 and Scenario B3 was shorter than that of Scenario B1, indicating that the same type of elderly people should be arranged on the same floor, which not only facilitated the care and help of medical personnel but also reduced the evacuation time in an emergency. Scenario B3 was shorter than the evacuation time used by Scenario B2, indicating that ECEP should be placed at the lowest level, and evacuation time could be shortened when an emergency occurred.

4.3. Impact of Property and Quantity of Elderly on Evacuation Time. ECEP was arranged at the bottom layer, and NAEP was arranged at the top layer, which effectively shortened the evacuation time. Therefore, the following model assumed that ECEP was at the bottom and NAEP was at the top. When the proportion of the elderly with different physical conditions was different, the evacuation time was also affected. The situation simulated above was the largest proportion of ECEP while the following assumed that the proportion of different types of elderly people was just the opposite. Table 9 shows that ECEP had the smallest number of people and NAEP had the largest number in Pathfinder software. Table 10 shows the distribution of the number of elderly people on each floor in Scenario C2 in Pathfinder software. The change in the number of people on each floor had an impact on the evacuation time. Scenario C3 was to reduce the number of people on each floor from 56 to 30, but the proportion of each type of old people and the living floor was the same as Scenario C1.

Figure 4 presents the simulation results of Scenarios C1, C2, and C3 when elevators were evacuated on different floors. The numbers 3–17 in the table referred to the use of elevators to evacuate from the 3rd floor to the 17th floor and the use of stairs for evacuation on other floors. The numbers 4–17 referred to the 4th floor to the 17th floor using elevator evacuation and other floors using stairs to evacuate. The number 0 means that the elderly on all floors were evacuated by stairs and no floors were evacuated by elevators. In this simulation, the priority of the elevator was from upper to lower floors.

The evacuation time used by Scenario C1 was always the longest. Scenario C2 had the fastest reduction in evacuation time when the number of layers used in the elevator was reduced. When the number of layers used in the elevator was on the 11th–17th floors, Scenario C2 reached the shortest evacuation time at 719 s. The evacuation time of Scenario C1 and Scenario C3 was similarly reduced, and both scenarios had the shortest evacuation time on the 13th–17th floors, and then the evacuation time continued to increase as the elevator used the number of layers. The simulation results

Table 6: Description of Scenarios B1, B2, and B3.

Scenario	Description
B1	Same as A5
B2	The old man living on the upper floor is from ECEP to NAEP
B3	The old man living on the lower floor is from NAEP to ECEP

Table 7: Number of different types of elderly people on each floor in Scenario B2.

Floor	Nurse	NAEP	SCEP	DCEP	MWEP	PWEP	ECEP	Total
3		56						56
4-5			56					56
6-7	2			54				56
8-9	2				54			56
10-11	2					54		56
12–17	2						54	56
Total	24	56	112	108	108	108	324	840
Proportion (%)	2.86	6.67	13.33	12.86	12.86	12.86	38.57	100.00

Table 8: Number of different types of elderly people on each floor in Scenario B3.

Floor	Nurse	NAEP	SCEP	DCEP	MWEP	PWEP	Evac + chair	Total
3–8	2						54	56
9-10	2					54		56
11-12	2				54			56
13-14	2			54				56
15-16			56					56
17		56						56
Total	24	56	112	108	108	108	324	840
Proportion (%)	2.86	6.67	13.33	12.86	12.86	12.86	38.57	100.00

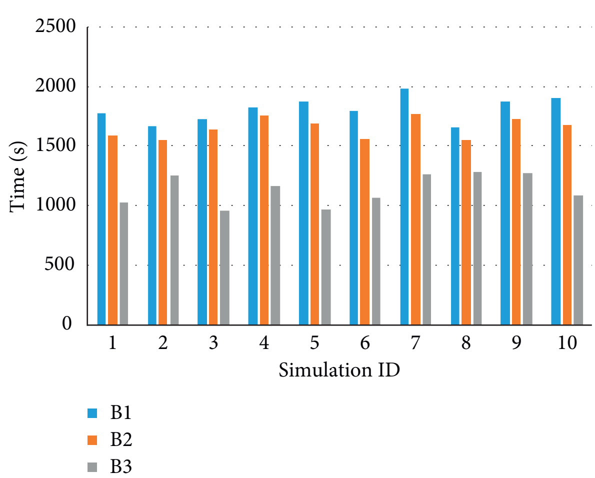


Figure 3: Occupant evacuation time of ten simulations in Scenarios B1, B2, and B3.

also demonstrated the need for a reasonable combination of elevator and stair evacuation. When the final evacuation time interval between the elevator and the stairs was small, the minimum time for evacuation was reached. Excessive use of elevators or stair evacuation could result in extended evacuation time. The longest evacuation time of the above three scenarios occurred when the number of elevators used was on the 3rd–17th floors, indicating that the use of elevators to evacuate all the elderly were the most unreasonable evacuation method. The shortest evacuation time of Scenarios C1, C2, and C3 were 852 s, 719 s, and 539 s, respectively, indicating that the number of elderly people with different physical conditions could affect the evacuation time. When the proportion of the elderly with the poor physical condition was high, the evacuation time increased. When the total number of elderly people living decreased, the evacuation time reduced.

4.4. Influence of Different Living Floors in High-Rise Nursing Home on Evacuation Time. Since most of the elderly people living in nursing homes were in poor physical condition needing the care from medical staff, the simulator set the largest proportion of ECEP and the smallest proportion of NAEP. Table 11 lists the description of different scene settings in Pathfinder software. Table 12 shows the representations when the number of elevators used in different scenarios was different. For instance, Case 1 indicated that Scenarios D1, D2, and D3 were evacuated by elevators on floors 6–13, 9–17, and 16–27, and stairs were used for evacuation on other floors. Case 2 indicated that Scenarios D1, D2, and D3 were evacuated by elevators on floors 7–13, 10–17, and 17–27 and evacuated by stairs on other floors. Figure 5 shows the evacuation time for each of the three scenarios. Figure 6 illustrates the relationship between the number of elderly people in nursing homes in Scenarios C1,

Table 9: Description of Scenarios B1, B2, and B3.

Scenario	Description
C1	Same as B3
C2	Number of people per floor is 56; the proportion of people is shown in Table 11
C3	Number of people per floor is 30; the proportion of people is shown in Table 8

Table 10: Number of different types of elderly people on each floor in Scenario C2.

Floor	Nurse	NAEP	SCEP	DCEP	MWEP	PWEP	ECEP	Total
3	2						54	56
4-5	2					54		56
6-7	2				54			56
8-9	2			54				56
10-11			56					56
12–17		56						56
Total	14	336	112	108	108	108	54	840
Proportion (%)	1.67	40.00	13.33	12.86	12.86	12.86	6.43	100.00

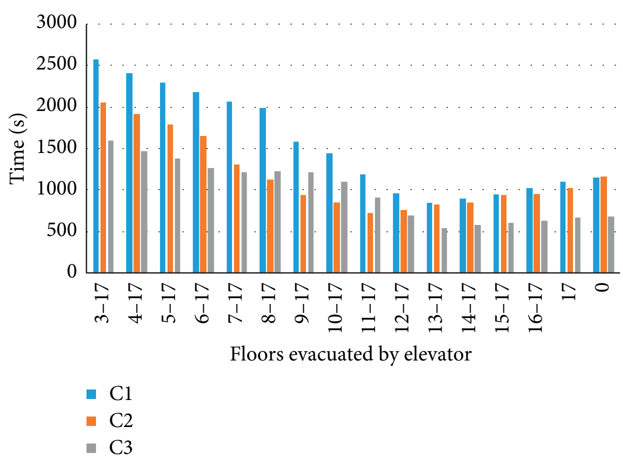


Figure 4: Occupant evacuation time of ten simulations in Scenarios C1, C2, and C3.

C2, C3, and D1 with the shortest evacuation time. The shortest evacuation time in Scenarios C1, C2, C3, and D1 were indicated when the number of layers used in the elevator was 13–17, 11–17, 13–17, and 10–13.

Figure 5 shows that the shortest evacuation time was proportional to the number of floor levels. As the number of floor levels increased, the minimum evacuation time increased. When the total number of floors in the nursing home building was 13, 17, and 27, the optimal number of floors for the elevator was floored 10–13, 13–17, and 20–27; the other floors were evacuated by stairs. Figure 6 illustrates that the trends of the number of elderly people in Scenarios C1, C3, and D1 were similar over time. When the proportion of different types of elderly people was the same, the evacuation efficiency of the elderly was also similar, regardless of the number of people on each floor and the number of floors. Scenario C2 had a slower evacuation speed in the first 400 s than Scenario C1 and quickly exceeded Scenario C1 after 400 s. During this period, the elevator was from the upper to the lower floors. The elderly on the upper floor of Scenario C2 was in good physical condition. Therefore, Scenario C2 was evacuated by the elevator in a short time, and the number of people was more than that of Scenario C1. However, the total number of people evacuated in the first 400 s of Scenario C2 was less than that of Scenario C1, indicating that the number of evacuated people in Scenario C2 was less than that in Scenario C1. The ECEP of the third layer of the first 400 s in Scenario C2 needed to wait for the assisting personnel to arrive. When the assisting personnel arrived, the personnel on the upper floor were evacuated to the third floor, and it was difficult for ECEP to enter the stairs. In Scenario C1, since the lower floors were all ECEP, other types of people in the upper layer did not arrive when the ECEP of the third layer was evacuated using stairs. Therefore, the ECEP of the following floors could be evacuated in an orderly manner. Although ECEP required a large delay time and a large footprint, the evacuation speed of ECEP was faster than that of other elderly people with the help of assisting personnel. Therefore, the number of the evacuation of Scenario C1 in the first 400 s was lower than that of Scenario C2.

4.5. Number of Floors on Optimal Elevator Use and Priority of Elevator Floor. The proportions of different types of old people in Scenarios C1, C3, D1, and D3 are the same. According to the analysis, the percentage of the total number of people using elevator evacuation in the shortest evacuation time in the four scenarios is shown in Table 13.

Percentage 1 in Table 13 refers to the percentage of the number of floors that were evacuated by the elevator to the total number of floors, and Percentage 2 refers to the percentage of the number of people who used the elevator evacuation to the total number of people. When the priority of the elevator-mounted floor was from the upper layer to the lower layer, the values of Percentages 1 and 2 of Scenarios C1, C3, D1, and D3 were identical as 29% and 33%, respectively. Scenario C2 had a different proportion of elderly people with different physical conditions. The percentage of people who used elevators to evacuate was 47%, which was different from the other four scenarios. When the

Table 11: The description of Scenarios D1, D2, and D3.

Scenario	Description
D1	The number of floors is 13 and the number of people on each floor is 56; the proportion of people is according to Table 8
D2	Same as C1
D3	The number of floors is 27 and the number of people on each floor is 56; the proportion of people is according to Table 8

Table 12: Representation of floors using elevators in different scenarios.

Scenario	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
D1	6–13	7–13	8–13	9–13	10–13	11–13	12–13	13	0
D2	9–17	10–17	11–17	12–17	13–17	14–17	15–17	16–17	17
D3	16–27	17–27	18–27	19–27	20–27	21–27	22–27	23–27	24–27

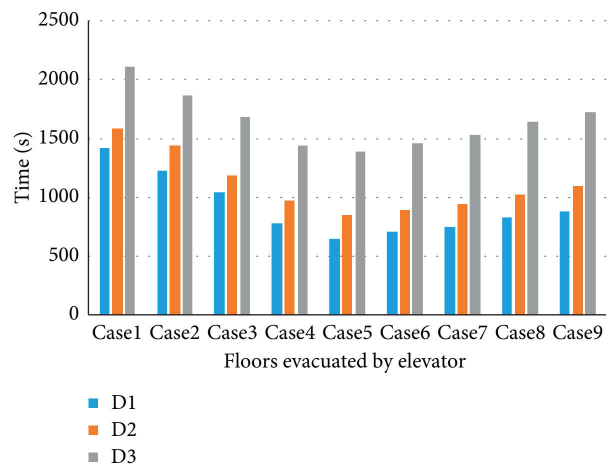


Figure 5: Occupant evacuation time of ten simulations in Scenarios D1, D2, and D3.

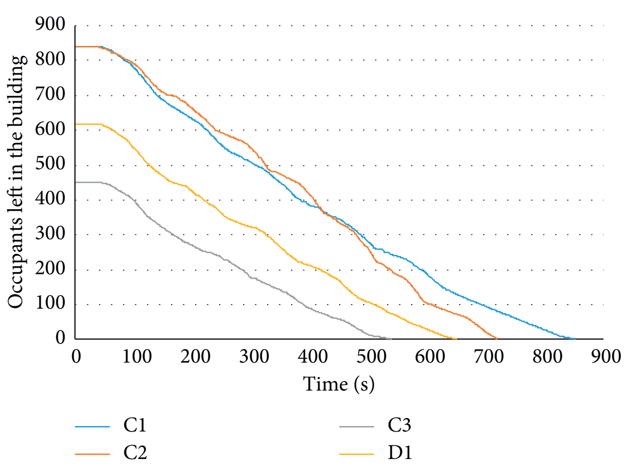


Figure 6: Curve of the number of elderly people in nursing homes over time.

proportion of the elderly with different physical conditions in nursing homes was the same, the proportion of the number of layers used by the elevators to the total number of floors and the number of people using the elevators was the total when the minimum evacuation time was reached. In emergencies, the optimal number of staying floors of the elevator in one nursing home could be set referring to other nursing homes with similar proportions, which could make the evacuation method efficient. Figure 7 shows the cumulative number of evacuations per door over time in Scenarios C1, C2, C3, D1, and D3 in the case of Table 13. Stairs 1 and 2 have the same size, and the elderly can choose the stairs to evacuate reasonably. Door 1 is an evacuation door for Stair 1, and Exit 2 is an evacuation door for Stair 2. The two curves are very close, indicating that the evacuation efficiency and cumulative evacuation times of the two stairs are almost the same. The difference between the cumulative evacuation number of Exit 1 and Door 1 is the cumulative evacuation number of elevators. Although the evacuation efficiency and cumulative evacuation number of elevators are higher than those of stairs, the cumulative evacuation time is the same as that of stairs. Stairs and elevators can maintain continuous evacuation throughout the evacuation process, achieving the best overall evacuation effect.

The priority of the elevator floor could affect the evacuation of the elderly. The above analysis assumed that the priority of the elevator floor was from the upper to the lower. Three scenarios were set in Table 14 to analyze the situation in Pathfinder software when the elevating floor priority of the elevator was from the lower layer to the upper layer. Figure 8 illustrates the evacuation time when the number of elevators was different in Scenarios E1, E2, and E3. Figure 9 shows the shortest evacuation time for Scenarios C1, C2, C3, E1, E2, and E3.

Figure 8 shows that when the priority order of the elevator was from the lower layer to the upper layer and the minimum evacuation time was reached, the number of elevators used in Scenarios E1, E2, and E3 was floors 3–5, 3–4, and 3–7, respectively, and the number of elevators used in Scenarios C1, C2, and C3 was floors 13–17, 11–17, and 13–17, respectively. In Scenario E, the underlying ECEP needed assistance from the facilitators; thus, the elderly needed to wait for the arrival of the facilitators in place, resulting in a delay. Because ECEP occupied a large position, it was very inflexible in the process of moving horizontally to the elevator. The movement into the elevator was slow, affecting the number of times the elevator was mounted. The large area of the ECEP caused the elevator to carry a small number of people per raft, which resulted in a longer time required for each floor of the elevator. Figure 9 shows that

Table 13: Relationship between the number of evacuated elevator evacuees and the total number of evacuees in the shortest evacuation time under Scenarios C1, C3, D1, and D3.

Scenario	Shortest evacuation time	Floors	Number of floors	Total number of floors	Number of elevator users	Total evacuees	Percentage 1	Percentage 2
C1	852	13–17	5	17	280	840	29	33
C2	719	11–17	7	17	392	840	41	47
C3	539	13–17	5	17	150	450	29	33
D1	650	10–13	4	13	224	616	31	36
D3	1391	20–27	8	28	448	1400	29	32

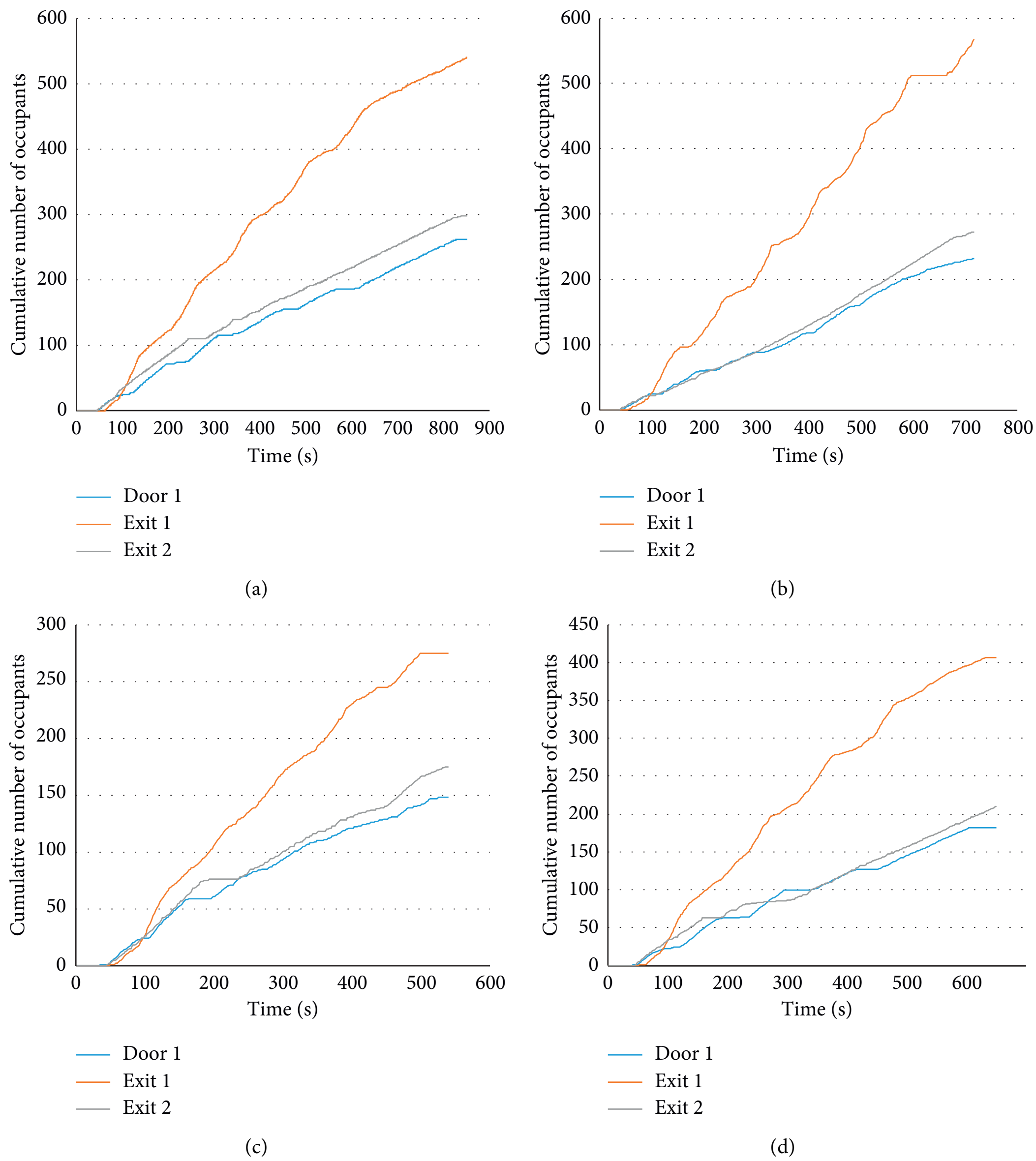
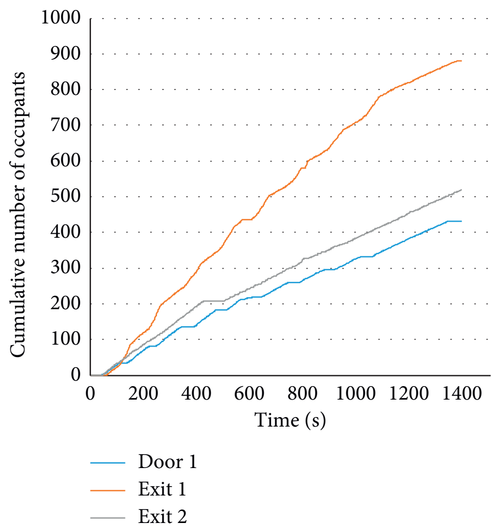


Figure 7: Continued.



(e)

FIGURE 7: The cumulative number of evacuations per door over time in Scenarios (a) C1, (b) C2, (c) C3, (d) D1, and (e) D3 in the case of Table 13.

TABLE 14: Description on Scenarios E1, E2, and E3.

Scenario	Description
E1	The number of people on each floor is 56; the proportion of the people is shown in Table 8
E2	The number of people on each floor is 56; the proportion of the people is shown in Table 11
E3	The number of people on each floor is 30; the proportion of the people is shown in Table 8

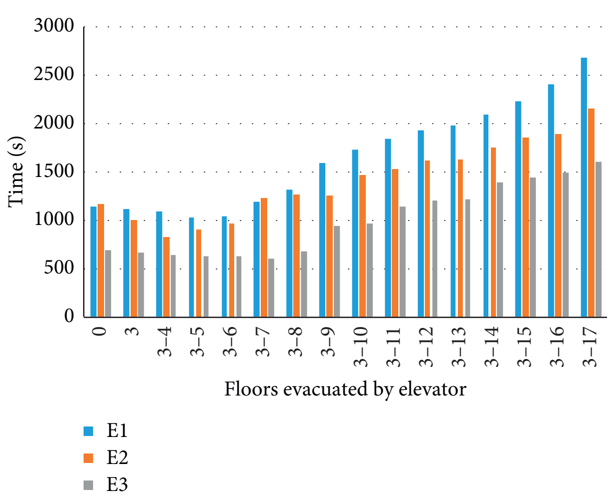


FIGURE 8: Occupant evacuation time of ten simulations in Scenarios E1, E2, and E3.

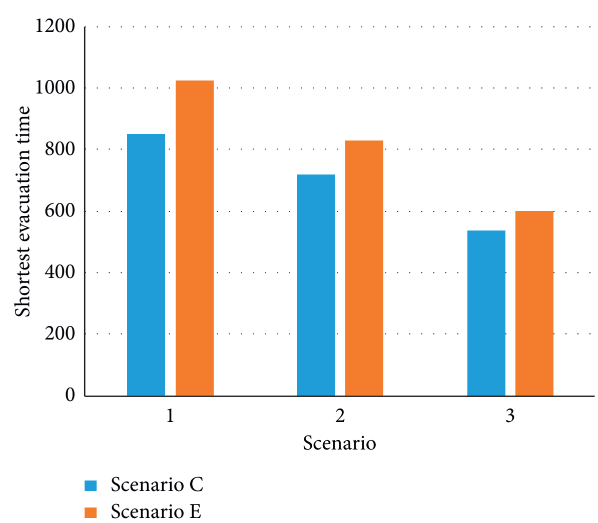


FIGURE 9: Minimum evacuation time for Scenarios C1, C2, C3, E1, E2, and E3.

the shortest evacuation time used in Scenarios C1, C2, and C3 was smaller than that of Scenarios E1, E2, and E3. Therefore, the priority order of the elevators was shorter from the upper level to the lower level than that from the lower level to the upper level, regardless of the physical condition of the occupants or the number of occupants on each floor.

4.6. Cumulative Number of Evacuations per Gate for Scenario C1 at the Shortest Evacuation Time. Figure 10 presents the cumulative evacuation number of each door as a function of time when the minimum evacuation time was reached and elevator evacuation was used when the number of floors used for elevator evacuation was 13–17 in Scenario C1. Figure 10 shows that all elderly people evacuated from Door

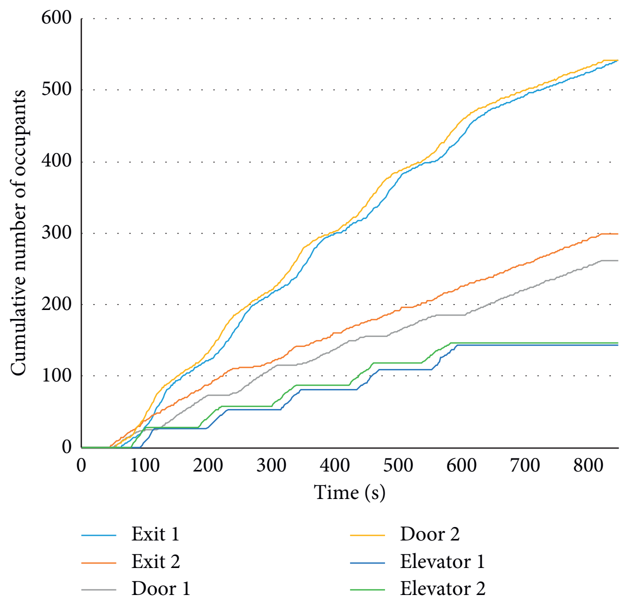


FIGURE 10: The cumulative number of evacuations per door over time.

2 entered Exit 1. The use of Stair 1 and elevators all reached Exit 1 through Door 1, causing great congestion in the elevator front room. Old people in the elevator could not get out of the elevator in time when they reached the ground floor. People evacuated through the stairs were too crowded to be evacuated to the exit in time. Therefore, the space in the front room of the elevator and the width of Door 2 should be increased. The trend of the evacuation curves of Exit 2 and Door 2 was similar, indicating that the evacuation efficiencies of the two stairs were similar. Elevator 1 and Elevator 2 had the same cumulative evacuation curve. At 600 s, the elevator was completed first, and then only two stairs were evacuated. The evacuation time through the two stairs was almost the same. Stair 1 had fewer evacuations than Stair 2 because Stair 1 needed to share the exit with the elevator when evacuating to the ground exit. If the exit was overcrowded, personnel would choose the best exit to avoid congestion. Therefore, the persons who originally chose Stair 1 would also change the evacuation route and chose Stair 2. According to the above analysis, it is necessary to increase the space of the common area in the elevator and the stairs and the width of the evacuation passage, to reduce the congestion and the evacuation time.

5. Conclusions

This study simulated the evacuation in a typical high-rise nursing home in several scenarios including the distribution of the elderly with different physical conditions, the proportion of the elderly in different physical conditions, the number of the elderly, the number of floors, the number of elevators used, and the priority of the elevator floor. By simulating the evacuation process in these scenarios, the general distribution strategy of high-rise nursing home and the optimal use of the elevator-stair combination during the emergency evacuation were developed. Results show that the elevator-stair combination of evacuation is more effective than using elevators or stairs alone. Increasing the number and speed of elevators can reduce evacuation time. Categorizing elderly people on each floor according to their physical conditions could reduce the evacuation time than randomly distributing them. Elderly people with better physical conditions are advised to be arranged on upper floors and those with worse physical conditions are to be arranged on lower floors to shorten the evacuation time. Although ECEP needs to wait for assistance personnel to arrive and takes up more space during the evacuation, it moves faster with the help of assistance personnel than other types of elderly people. Pacing ECEP on high floors could generate a reverse flow, causing the stairs to be blocked. The evacuation efficiency of elderly people was not affected by changing the total number of floors. When the proportion of different types of elderly people was fixed, the trend of the relationship between evacuation number and time was consistent, regardless of the number of floors and the number of people on each floor. The longest evacuation time was used when the elevator started from the lower layer to the upper layer, and the shortest evacuation time was used when the elevator started from the upper layer to the lower layer. In the future simulation, modern facilities such as life slides could be considered to combine with stairs and elevators for emergency evacuation.

Data Availability

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

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Chen Wang conceptualized the study; Yameng Chen carried out the methodology; Jeffrey Boon Hui Yap prepared and wrote the original draft; Heng Li validated the study; Hong Song Hu helped with the software; Chih-Cheng Chen validated and wrote the article, review and editing; and Kuei-Kuei Lai wrote the article.

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