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ABSTRACT

Due to patient vulnerability and the diversity of personnel, hospital inpatient evacuations are more prone to congestion and even stagnation, making fire evacuation in hospital wards more complex and hazardous than in other buildings. Most existing studies focus solely on evacuation, neglecting the impact of fire scenarios on the evacuation process. To provide more comprehensive insights into high-rise hospital ward fire evacuations, this study takes the inpatient department of a secondary hospital in China as a case study. Multiple fire scenarios were simulated using PyroSim software, and parameters including temperature, visibility, and CO concentration were analyzed to determine the available evacuation time. Based on the building layout and occupant distribution, several evacuation strategies were designed and compared through simulations using Pathfinder software, ultimately identifying the optimal evacuation strategy. The results indicate that evacuation efficiency can be significantly improved by rationally adjusting exit selection, setting occupant priority, and implementing refuge areas. Moreover, evacuation strategies should be appropriately modified and optimized according to the location of the fire source. The findings of this study provide practical strategies for fire evacuation in high-rise hospital wards, effectively reducing casualties and contributing to the safety management of such facilities.

Keyword:

Hospital inpatient wards； Fire simulation; Personnel evacuation; Strategy optimization

1. Introduction

In recent years, the number of public medical facilities, including general hospitals, teaching hospitals, and specialized hospitals, has been steadily increasing, accommodating a growing number of patients and providing greater convenience to the public. By the end of 2023, the total number of hospitals in China had reached 38,000 [1]. However, emergencies in high-density public spaces and inherent safety hazards in public buildings pose significant threats to human life. For instance, in May 2018, a fire occurred at a hospital in Jiangning District, Nanjing, resulting in 9 deaths and 35 injuries. In April 2019, a fire broke out in the east ward of the Fifth People's Hospital in Quanzhou, Fujian Province, causing 21 burn injuries, including 7 severe cases. When high-rise hospitals face sudden emergencies, rapid evacuation to safe areas is required, which can easily lead to crowding and even stampede incidents. In particular, during a fire, buildings are filled with high-temperature smoke, which severely impedes safe evacuation. High-rise hospitals face unique challenges due to their specific characteristics, including patient vulnerability, complex environments, and higher occupant density, making fire evacuation in these facilities more complex and difficult [2]. Therefore, it is essential to develop efficient and rational evacuation strategies to enhance evacuation efficiency and ensure occupant safety.

Research on fire dynamics in high-rise buildings has a long history [3]. The core hazards of such fires lie in their rapid vertical spread, greatly increased evacuation difficulty, and limited firefighting and rescue access. In specialized settings such as medical facilities, differences in patients' mobility can reduce evacuation efficiency by 40%–60%. During a fire, combustion by-products pose severe threats to human health, further complicating evacuation [4, 5]. Studies by Yan et al. [6] found that visibility and high temperature had significant effects on evacuation. Zhang et al. [7] investigated cruise ship fires with five different ignition locations and reported that, regardless of the fire source position, visibility had the greatest impact on the available safe egress time. Zheng et al. [8] investigated fires in libraries and found that during a fire, as smoke spreads rapidly, visibility has an increasingly significant impact on evacuation. Numerous studies have indicated that, regardless of building type, reduced visibility is typically the most critical factor affecting evacuation during fires.

A review of building evacuation studies has found that occupants located on upper floors are more prone to fatigue during evacuation, and narrow exits and corridors can lead to congestion due to the accumulation of evacuees [9]. Obstructions placed in corridors and stairwells reduce the effective width of evacuation routes, thereby slowing the evacuation process [10]. Fan et al. [11] conducted a fire evacuation simulation in a large factory workshop and found that the main factors affecting evacuation were exit width, stair width, and occupant distribution. The results indicated that changing the exit width alone had little effect on evacuation time, whereas increasing the effective evacuation width of stairs could significantly relieve evacuation pressure. When the stair width increased by 0.5 m, the evacuation time decreased by 30.0 s. Hu et al. [12] investigated fire scenarios involving people with disabilities in a historical museum and found that individuals with limited mobility moved more slowly, which easily caused congestion among evacuees behind them and consequently prolonged evacuation time.

For existing buildings, modifying the physical structure can be challenging. However, evacuation strategies can be tailored to the occupant types and building layout to reduce evacuation time. Lin et al. [13] conducted an evacuation simulation of a hospital building using Pathfinder and proposed several strategies, including setting evacuation priorities, optimizing vertical functional zoning, adjusting exit locations, and improving stair design, which effectively reduced the required evacuation time. Fang et al. [14] reported that the highest evacuation efficiency could be achieved when occupants with the weakest evacuation capability were located on the lowest floors, those with the strongest evacuation capability were located on the middle floors, and those with moderate evacuation capability were located on the highest floors. With the continuous development of firefighting elevator technology, the use of elevators during evacuation has become feasible. Fang et al. [15] proposed an intelligent elevator-assisted evacuation scheme for building fires and presented three evacuation strategies. The results showed that for high-density super high-rise buildings (36 and 48 floors), the optimal strategy was for part of the occupants on each floor to evacuate using elevators while others used stairs. For medium–high-rise buildings (12 and 24 floors), a strategy in which occupants above certain floors used elevators was more appropriate. For super high-rise buildings (36 and 48 floors) with low occupant density on each floor, a strategy involving refuge floors with elevators stopping only at these refuge floors was more suitable. Enrico

Ronchi et al. [16] simulated two adjacent 50-story office buildings and found that evacuation strategies using evacuation elevators alone, as well as combined strategies involving elevators, stairs, and skybridges, resulted in shorter evacuation times. Although these studies proposed different evacuation strategies for various building types, they did not consider evacuation under special conditions such as fires occurring within buildings. When a fire occurs, the evacuation process becomes more complex, and occupants must evacuate safely within the available safe egress time.

Previous studies on fire and evacuation are relatively comprehensive; however, research on fire evacuation for mobility-impaired individuals remains limited, especially in high-density and complex public facilities such as hospitals. This study focuses on vertical evacuation strategies under different fire scenarios, using PyroSim to simulate fire dynamics [17] . Three fire scenarios were studied to determine the available safe evacuation time. Subsequently, Pathfinder was used to simulate occupant evacuation, and five evacuation strategies were proposed. By integrating the fire simulation results, the optimal evacuation strategy was identified, reducing both evacuation time and casualties.

2. Methods

2.1 Research Framework

Fig. 1 illustrates the research process of this study. First, a BIM model was established based on the building's physical parameters and imported into PyroSim for fire dynamics simulation. For three fire source locations, smoke spread, temperature, and CO concentration were simulated to calculate the Available Safe Evacuation Time ($ASET$). Subsequently, multiple occupant evacuation scenarios were designed and simulated using Pathfinder, and the Required Safe Evacuation Time ($RSET$) for each strategy was compared. Finally, the optimal evacuation strategy was determined.

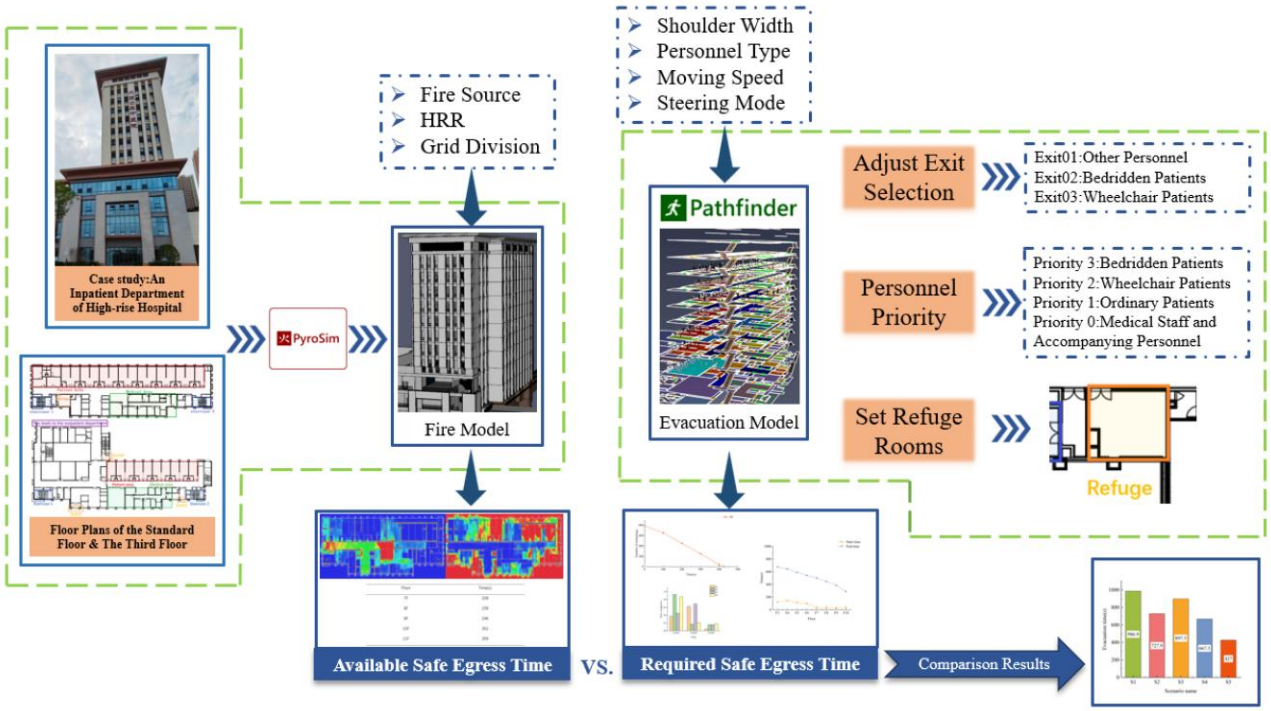


Fig. 1. Work frame of this paper.

2.2. Case Study Building

This study takes the inpatient department of a secondary hospital in southwestern China as a case study. The hospital building has 12 above-ground floors and one basement, with a total height of 57.8 m and a first-level fire protection rating. Floors 1–2 are designated for outpatient services, floor 5 for surgical operations, and floor 12 for administrative offices. Floors 3–4 and 7–11 serve as inpatient wards, with the left side of floor 6 allocated to patient rooms and the right side to maternity wards. Based on field investigation, the inpatient department contains a total of 300 beds, nine stairwells, and eleven safety exits. In the evacuation simulations, only two stairwells within the inpatient department (each 1.6 m wide) and three dedicated exits on the third floor of the inpatient department (each 1.8 m wide) were used. The exact locations of the exits are shown in Fig. 2. The typical floor plan for floors 7–11 is also shown in Fig. 2, comprising seventeen wards, with the two leftmost rooms serving as backup wards.

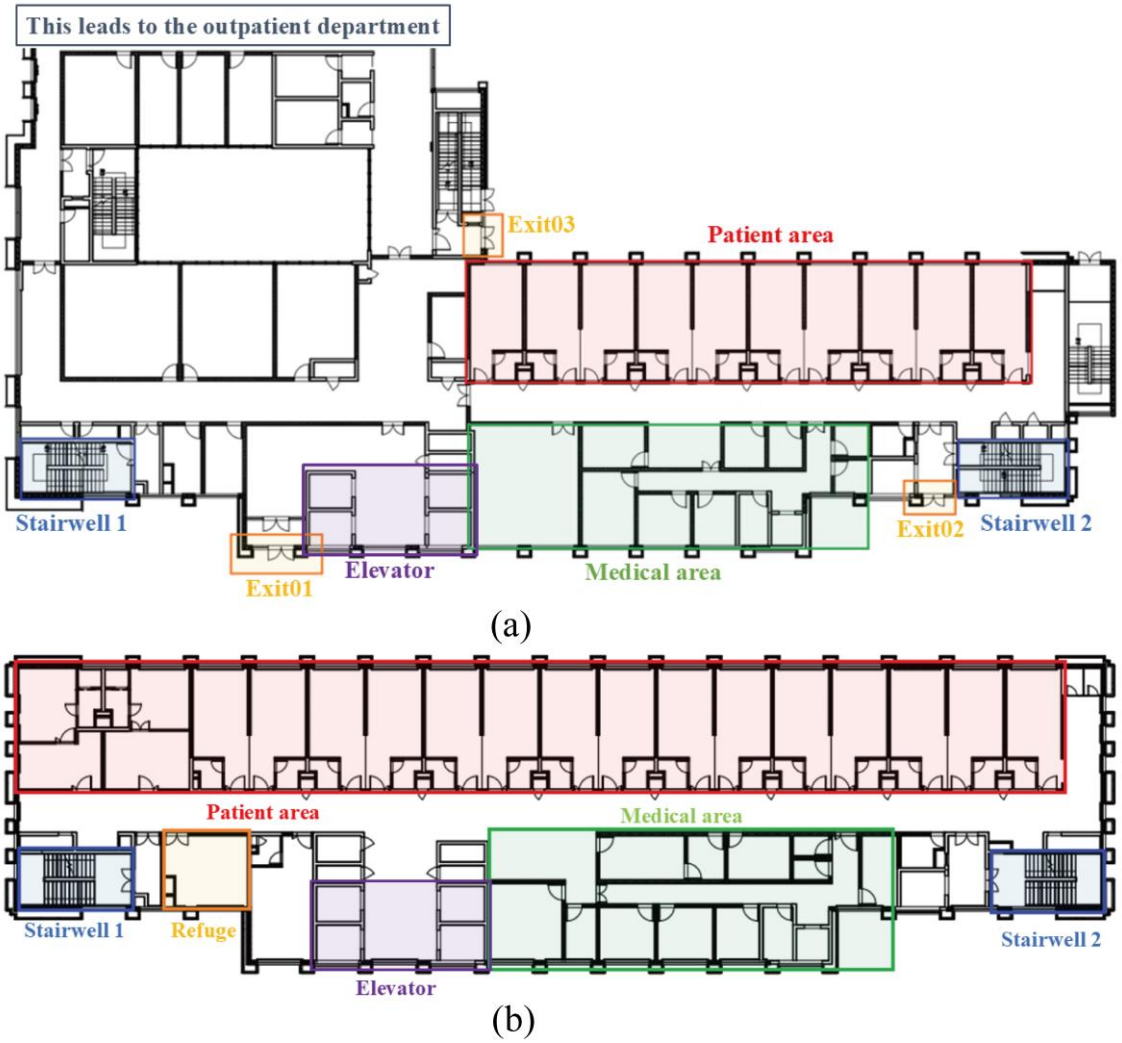


Fig. 2. Floor plan. (a)Three-storey floor plan, (b)Standard Floor Plan.

2.3. Fire Simulation Parameters

2.3.1. Fire Source Settings

Occupants are primarily concentrated on floors above the sixth floor. To investigate the impact of fire on heavily populated upper floors, the fire source in this study was set on the sixth floor. The fire was assumed to originate from an overloaded lighting circuit that had been in prolonged operation, resulting in ignition.To examine the effects of fire location on evacuation, three fire scenarios were designed: Scenario A, with the fire located between the two stairwells; Scenario B, with the fire near the entrance of Stairwell 1; and Scenario C, with the fire near the entrance of Stairwell 2. The specific fire source locations are shown in Figure 3. The fire source dimensions

were set to 1 m × 1 m × 1 m, and the initial ambient temperature was 20°C. This study does not consider the pre-ignition stage of the fire, assuming that the fire begins from the onset of effective combustion. Therefore, the heat release rate (HRR) is calculated using the following (Eq.(1)):

$$Q = \alpha t^2 \tag{1}$$

where Q is the heat release rate, in kW, α is the fire growth rate coefficient, in kW/s^2, t is the fire development time, in s.

Based on the variation in the heat release rate, α is categorized into four types. In this study, due to the presence of a large number of wooden furniture and cotton textiles within the building, the fire type was set as a fast fire, for which the value of α is $0.04689 kW/s^2$.

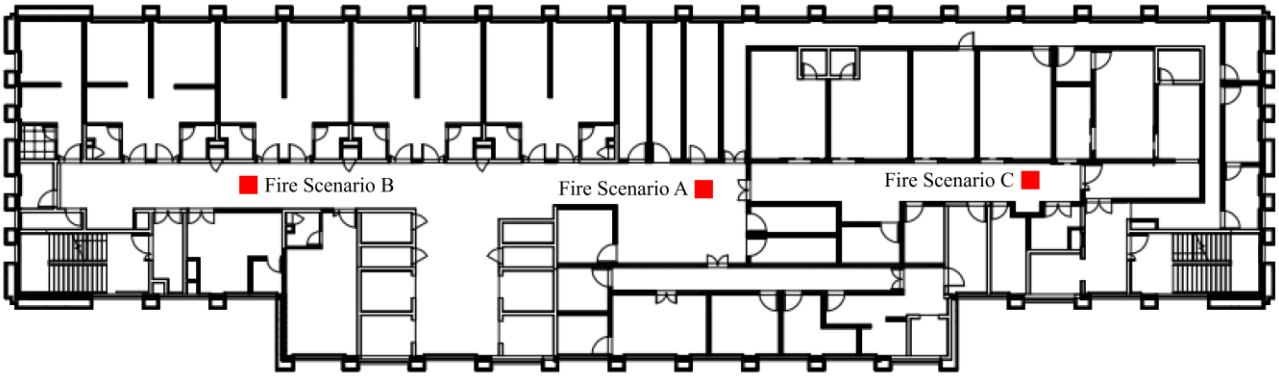


Fig. 3. Fire source locations.

2.3.2. Grid Partitioning

Prior to fire simulation, the building model must be discretized into a computational grid. Grid design should balance accuracy and computational efficiency. A finer grid increases calculation precision but significantly prolongs computation time or may even prevent the simulation from running, reducing efficiency. Conversely, an overly coarse grid can lead to simulation bias. The grid size is determined by the characteristic diameter of the fire source, D^*, and is typically set between 1/16 and 1/4 of D^*. The characteristic diameter of the fire source, D^*, is calculated using (Eq.(2)) [6]:

$$D^* = \left(\frac{Q}{\rho_\infty C_P T_\infty \sqrt{g}} \right)^{\frac{2}{5}} \tag{2}$$

Where D^* is the characteristic diameter of the fire source, in m, Q is the heat release rate of the fire

source, in kW, ρ_∞ is the air density, taken as $1.2kg/m^3$, C_P is the specific heat capacity of air, taken as $1kJ/(kg \cdot K)$, T_∞ is the initial indoor temperature, taken as $293K$, g is the gravitational acceleration, taken as $9.8m/s^2$.

According to the *Technical Standard for Smoke Control and Exhaust Systems in Buildings* (GB 51251-2017) [18], and referring to the requirements for public places with sprinklers, the maximum heat release rate of the fire source in this study was set to 2.5 MW. The characteristic diameter (D^*) was calculated to be 2.2 m using Eq.(2). Therefore, considering both accuracy and computational efficiency, the simulation grid size was set to 0.5 m.

2.4. Critical Thresholds of Fire Hazard Factors

Toxic gases, high-temperature smoke, reduced oxygen levels, and excessively thick smoke layers in fire environments hinder evacuation and pose serious threats to human health, potentially resulting in injury or death. [19]. Analysis of casualties in building fires indicates that the primary causes are smoke toxicity, hypoxia, and thermal injury. Among these, smoke temperature, carbon monoxide (CO) concentration, and visibility are the most critical factors. [20]. Therefore, the hazardous conditions of a fire can be assessed by analyzing the critical tolerance thresholds of humans to these factors.

2.4.1. Smoke Layer Height

Fire smoke contains a large amount of particulate matter and toxic decomposition products, which pose significant hazards to building occupants. During a fire, high-temperature smoke rises to the top of the building under the effect of thermal buoyancy and accumulates to form a smoke layer. As smoke continues to increase, the smoke layer descends, potentially impeding evacuation. During evacuation, it is essential to prevent direct contact between evacuees and hot smoke, maintaining a safe distance between the occupants and the smoke layer. The height of the smoke layer during evacuation should satisfy (Eq.(3)) [21]:

$$H_S \geq H_C = H_P + 0.1H_B \tag{3}$$

where H_S is the height of the smoke layer, in m, H_C is the critical danger height, in m, H_P is the

average height of occupants, typically 1.6 m, H_B is the average height of each storey in the building, in m.

The average floor height of the hospital building is 3.2 m. According to the calculation, the critical height $H_C$is 1.93 m; therefore, in this study, the hazardous critical height of the smoke layer is set at 2 m above each floor level.

2.4.2. Flue Gas Temperature

During a fire, a large amount of heat spreads along with smoke throughout the building. As the fire intensifies, high-temperature smoke continues to propagate, transferring heat to the surrounding air through thermal radiation from upper to lower floors, causing air temperatures to rise. When the temperature of the lower-floor air exceeds human tolerance thresholds, it poses a direct hazard to occupants. Studies have shown that direct exposure to high-temperature air can cause thermal shock and skin burns, which are closely related to the moisture content in the air, as summarized in Table 1. In this study, the critical temperature threshold is set at 60 °C [22].

Table 1

Human tolerance limits for high-temperature gases.

Temperature（℃）	Humidity	Endurance Time（min）
<60	Well-watered	>30
60	Moisture content<1%	12
100	Moisture content<1%	1

2.4.3. Concentration of CO in Flue Gas

During evacuation, the primary cause of casualties due to carbon monoxide (CO) is that CO enters the body through respiration and binds with hemoglobin in the blood, impairing respiratory and neurological functions. The binding affinity of CO to hemoglobin is nearly 200 times greater than that of oxygen, preventing oxygen from binding and leading to poisoning and asphyxiation, which can be fatal. Table 2 summarizes the effects of CO on human health [23]. Based on the severity of the

hazard, a CO concentration of 500 ppm is selected in this study as the critical threshold for danger.

Table 2

Effects of carbon monoxide on the human body.

CO content(ppm)	Level of hazard
200	2-3 hours, mild headache, fatigue
500	1-2 hours, headache; 3 hours, life-threatening
800	45 minutes, nausea, cramps; 2 hours, loss of consciousness; 2-3 hours, death
1600	20 minutes, dizziness, nausea; 25-30 minutes, death
3200	2-10 minutes, headache, nausea; 15-20 minutes, death

2.4.4. Visibility

During a fire, the combustion of flammable materials produces numerous particulate matter suspended in the smoke. These particles reduce visibility by obscuring light, hindering occupants' line of sight and impairing their ability to perceive the surrounding environment. The *SFPE Handbook of Fire Protection Engineering* suggests that [24], considering building layout and human behavior during a fire, a visibility of 13 m allows occupants to evacuate safely, although the size of the space also affects the critical visibility threshold. The Australian *Fire Engineers' Guide* specifies critical visibility values for spaces of different sizes, as summarized in Table 3.

Table 3

Visibility thresholds.

Scene	Small spaces(floor area<100m^2)	Large space(floor area>100m^2)
Visibility（m）	5	10

In summary, since most rooms in the hospital inpatient department are relatively small, a critical visibility limit of 5 m is adopted, serving as the standard for the safe visual range at eye level for occupants.

2.4.5. Determination of available evacuation time

The safe evacuation of occupants during a fire depends on two factors: the Available Safe Evacuation Time (T_{ASET}) and the Required Safe Evacuation Time (T_{RSET}). Evacuation is considered safe only if T_{RSET} is less than T_{ASET}. Based on the analysis of the hazardous factors affecting occupant safety, if any of these factors exceed the thresholds listed in Table 4, safe evacuation cannot be achieved. Therefore, evacuation or movement away from the hazardous area must be completed before this point.

Table 4

Conditions for a fire to reach a dangerous state.

Risk factors	Threshold
Temperature	At a height of 2 metres above the floor level on each storey, the flue gas temperature reaches 60°C or above.
CO concentration	At a height of 2 metres above the floor level on each storey, the CO concentration in the smoke exceeds 500 ppm.
Visibility	Visibility less than 5 metres at a height of 2 metres above the floor level on each storey.

2.5. Evacuation simulation parameters

2.5.1. Assumptions

The following assumptions are made for the simulation of occupant evacuation in the hospital inpatient department::

（1） After reaching the safe area, all occupants are assumed not to return. Medical staff are responsible for evacuating bedridden patients, while wheelchair-bound patients are assisted by their caregivers. Fig. 4 illustrates the evacuation methods for wheelchair-bound and bedridden patients.

（2） Each patient is accompanied by one caregiver, and all caregivers are assumed to be healthy adult males or females.

（3） Group effects are not considered, such as interactions between caregivers and patients. Except for the small-group effect between helpers and mobility-impaired patients, all other occupants are assumed to evacuate independently.

（4） The evacuation response time is assumed to be 60 s, which includes the time required to respond after hearing the alarm and the preparation time for evacuating bedridden and wheelchair-bound patients. That is, all evacuees begin evacuation 60 s after the fire occurs.

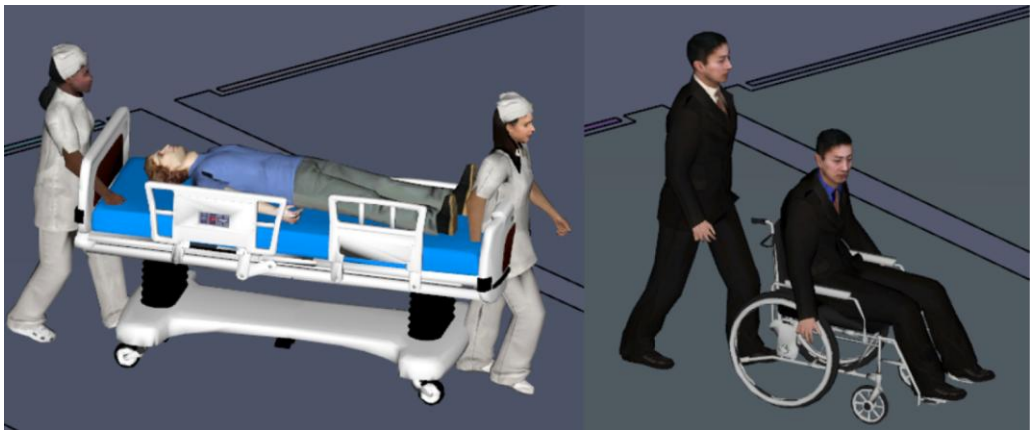


Fig. 4. Evacuation methods for bedridden and wheelchair patients.

2.5.2. Evacuation personnel parameter settings

The inpatient department of the hospital is a relatively densely populated area. Based on the actual number of beds, field investigation, and on-site statistics, the total number of evacuees was determined, as detailed in Table 5. Among them, 30% of patients are immobile, 13% are bedridden, and 17% use wheelchairs, with a male-to-female ratio of 1:1. Floors 3–4 have 2 beds per room, floor 6 has 2–3 beds per room, and floors 7–11 have 3 beds per room. All patients are located within the wards, and caregivers remain near the patients, while medical staff are randomly distributed. The staff-to-bed ratio is based on the *National Medical Service System Planning Outline (2015–2020)*, set at 1:0.6 [25], a total of 187 medical staff members are included in the simulation, with two nurses assigned per ICU bed. Among them, male nurses account for 3% of the staff [26].

Table 5

Personnel statistics.

Floor	Number of patients	Number of accompanying persons	Number of healthcare personnel	total
3F	20	20	12	52
4F	22	22	16	60
5F	4	4	8	16
6F	22	22	13	57
7F	52	52	30	134
8F	45	45	27	117
9F	45	45	27	117
10F	45	45	27	117
11F	45	45	27	117
total	300	300	187	787

Evacuation speed is influenced by factors such as gender and age, with males generally moving faster than females. Based on the study by Jiang et al. on occupant evacuation speeds during fires in large hospitals [27], the evacuation speeds used in this study are listed in Table 6. The speeds for wheelchair-bound and bedridden patients are set according to the findings of D'Orazio et al. [28]. The physical attributes of evacuees are determined based on the *Chinese Adult Body Dimensions (GB/T 10000-2023)* [29], *Wheelchairs—Part 2: Typical Values and Recommended Limits for Dimensions, Mass, and Operating Space Measured According to GB/Z 18029.5* [30] , and the *People's Republic of China Industry Standard: Hospital Beds (YY 0003-90)*.

Table 6

Physical attributes of evacuees.

Personnel category		Speed(m/s)	Shoulder width / length × width(m)
Adult male	Normal	1.01~1.3	0.42~0.48
	Patient	0.9~1.1	
Adult female	Normal	0.9~1.2	

Patient	0.75~0.95	
Wheelchair patients	0.6~0.8	1.0*0.7
Bedridden patients	0.4~0.6	2.15*1.0

2.5.3. Behavioural Pattern Settings

Pathfinder software provides two behavioral modes: SFPE and Steering. The SFPE mode, based on the SFPE Handbook of Fire Protection Engineering, determines movement speed according to spatial density, with occupants automatically moving toward the nearest exit, making it suitable for simple evacuations. The Steering mode combines path-planning algorithms with collision handling to control occupant movement. If the distance between individuals and the path to the nearest exit exceeds a certain threshold, a new path is generated, allowing for a more realistic representation of dynamic adjustments and collisions among evacuees. Therefore, the Steering mode is adopted in this study for the simulation.

2.5.4. Evacuation Scenario Settings

Five evacuation scenarios are established in this study:

Scenario 1 (S1) represents unorganized evacuation, in which no intervention is applied to the evacuees. This scenario serves as a control group for comparison with other evacuation strategies.

Scenario 2 (S2) involves differentiated evacuation, where occupants of different types use designated exits. Due to the building layout, most occupants evacuating via Exit 01 and Exit 03 use Stairwell 1, while those evacuating via Exit 02 use Stairwell 2. Bedridden patients, who are more difficult to evacuate and prone to causing congestion, are directed to evacuate through Exit 02 to minimize their impact on the evacuation of others. Wheelchair-bound patients, being fewer in number, evacuate through Exit 03. The assignment of exits is summarized in Table 7.

Table 7

Evacuation exit selection for S2.

Exit	Types of evacuees

Exit 01	Evacuees other than bedridden patients and wheelchair users
Exit 02	Bedridden patients
Exit 03	Wheelchair patients

Scenarios 3 (S3) and 4 (S4) are based on S1 and S2, respectively, with the addition of priority levels for occupants. The priority assignments are listed in Table 8, where higher values indicate higher priority. When an individual encounters another with the same priority, their state remains unchanged. If an individual encounters someone with a higher priority, they yield and allow the higher-priority individual to pass first. Conversely, when encountering someone with lower priority, the individual may push or bypass them to maintain priority passage [13]. For medical staff and caregivers assisting bedridden or wheelchair-bound patients, their priority is elevated to match that of the individuals they are assisting, as shown in Table 8.

Table 8

Priority settings.

Personnel category	Bedridden patients	Wheelchair patients	Ordinary patients	Medical staff and accompanying personnel
Priority	3	2	1	0

Scenario 5 (S5) incorporates refuge areas, as stipulated by the Code for Fire Protection Design of Buildings, which requires that inpatient floors above the second floor in high-rise hospital buildings be equipped with refuge areas. Each refuge area should serve no more than two nursing units, have a minimum net area of 25 m^2, and be located near stairwells [31]. Accordingly, in this study, refuge areas are established on floors above the third floor, each with an area of 25 m². Once evacuees reach a refuge area, they are considered to have completed evacuation. The locations of the refuge areas are shown in Fig. 2.

3. Results and Discussion

3.1. Fire Simulation Results

3.1.1. Simulation Results of Fire Scenario A

The smoke distribution slices are shown in Fig. 5. The results indicate that floors at and above the fire source are affected by smoke, while floors below the fire source remain largely unaffected. After the fire occurs, smoke initially accumulates above the fire source and then spreads laterally throughout the building. At 300 s, the smoke has already spread through the elevator shaft to the 12th floor. By 500 s, more than half of the building area is filled with smoke.

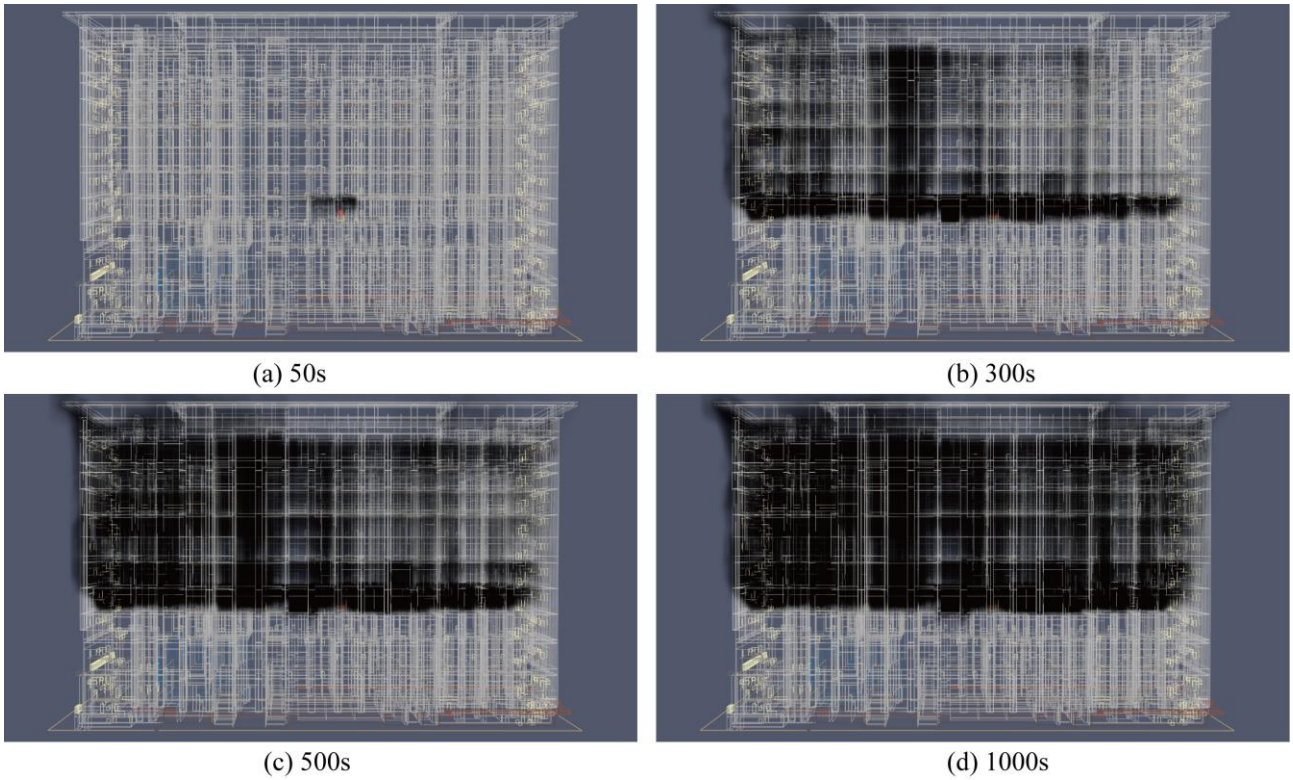


Fig. 5. Smoke evolution in fire scenario A.

In the early stages of the fire, temperatures near the fire source rise rapidly and gradually stabilize over time. The temperature slices at 2 m above the floor are shown in Fig. 6. At 100 s after the fire ignites, temperatures near the fire source exceed 60°C, surpassing the human tolerance limit. The temperature near Stair 1 reaches 60°C at approximately 200 s. After 300 s, the area between Stair 1 and the fire source is classified as a hazardous zone and can no longer be used for evacuation.

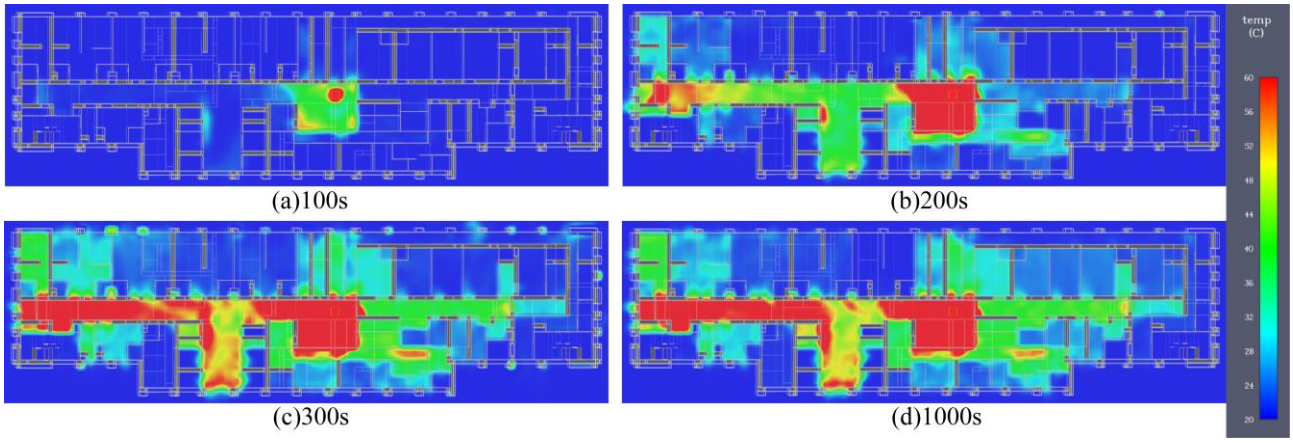


Fig. 6. Temperature field variation on the sixth floor under fire scenario A.

During the entire fire scenario, only the area near the fire source on the sixth floor exhibits CO concentrations exceeding 500 ppm, while CO levels in all other areas remain below the human tolerance limit.

Fig. 7 presents visibility slices at 2 m above the floor on the sixth floor. At 100 s after the fire ignition, visibility near the fire source drops below 5 m. Around 150 s, visibility at the entrance of Stair 1 falls below 5 m. By 250 s, no safe areas remain within the sixth-floor corridor. Therefore, evacuees on the sixth floor should leave the vicinity of the fire source within 100 s. Those using Stair 1 should enter the stairwell before 150 s, while those using Stair 2 should enter before 250 s.

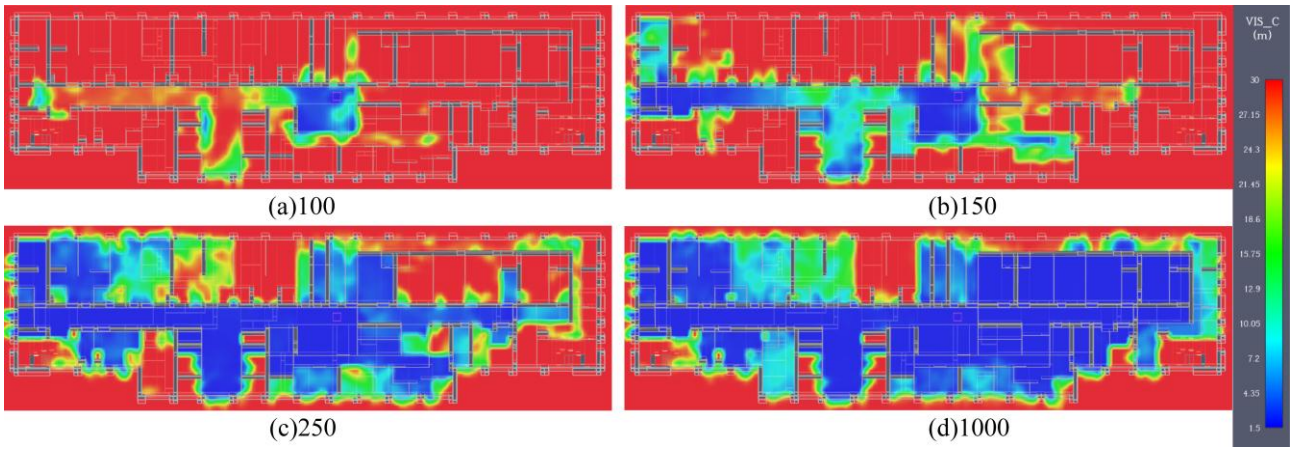


Fig. 7. Visibility distribution on the sixth floor under fire scenario A.

3.1.2. Simulation Results of Fire Scenario B

Fig. 8 Figure 8 illustrates the smoke distribution for Fire Scenario B, which shows a dispersion pattern similar to that of Scenario A. CO concentrations exceed 500 ppm only at the fire source, while

other areas remain within human tolerance limits. The fire source in Scenario B is located in a narrower corridor, resulting in faster temperature rise and more rapid visibility reduction near the fire source. The temperature at the fire source reaches 60°C at 61 s, and by 142 s, the area between the fire source and Stair 1 exceeds 60°C, whereas the entrance to Stair 2 remains within the safe temperature range. Visibility near the fire source, at the entrance of Stair 1, and at the entrance of Stair 2 drops below 5 m at 68 s, 90 s, and 166 s, respectively. The temporal variations of temperature and visibility on the sixth floor for Scenario B are shown in Fig. 9 and Fig. 10.

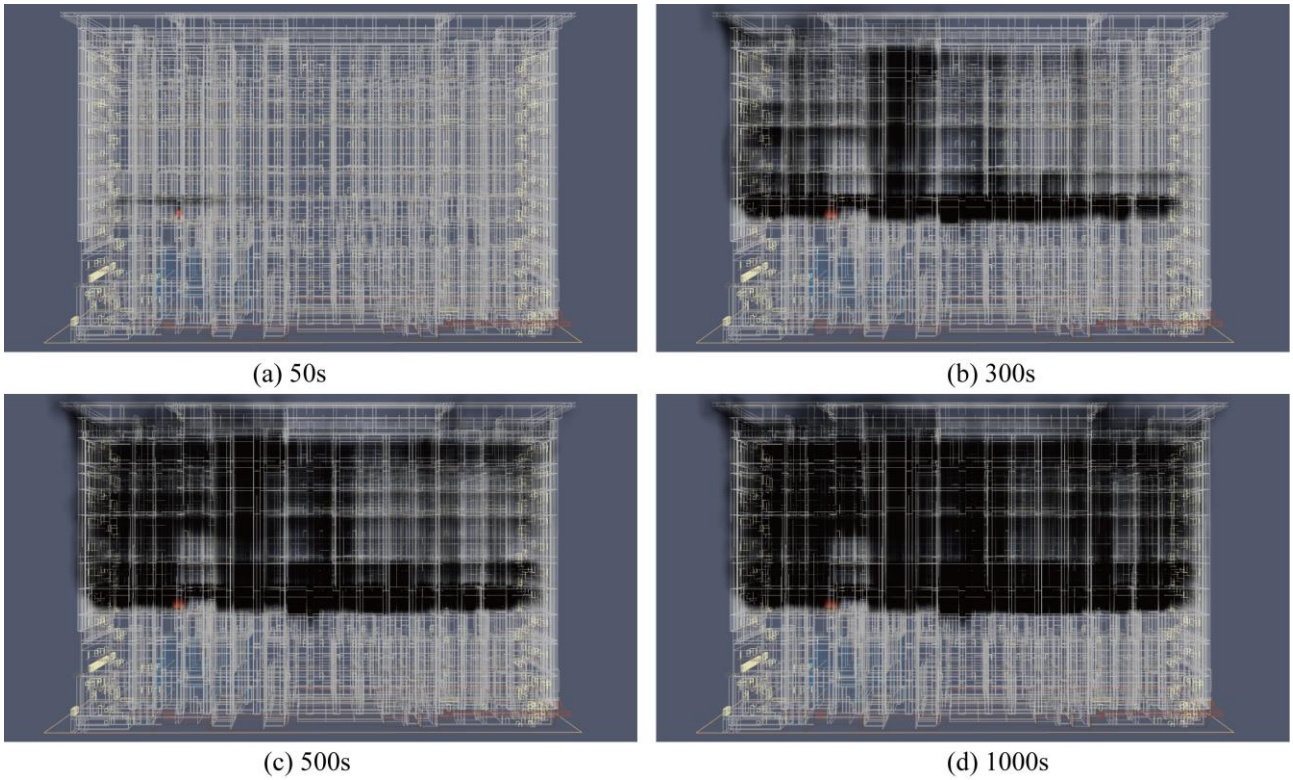


Fig. 8. Smoke evolution in fire scenario B.

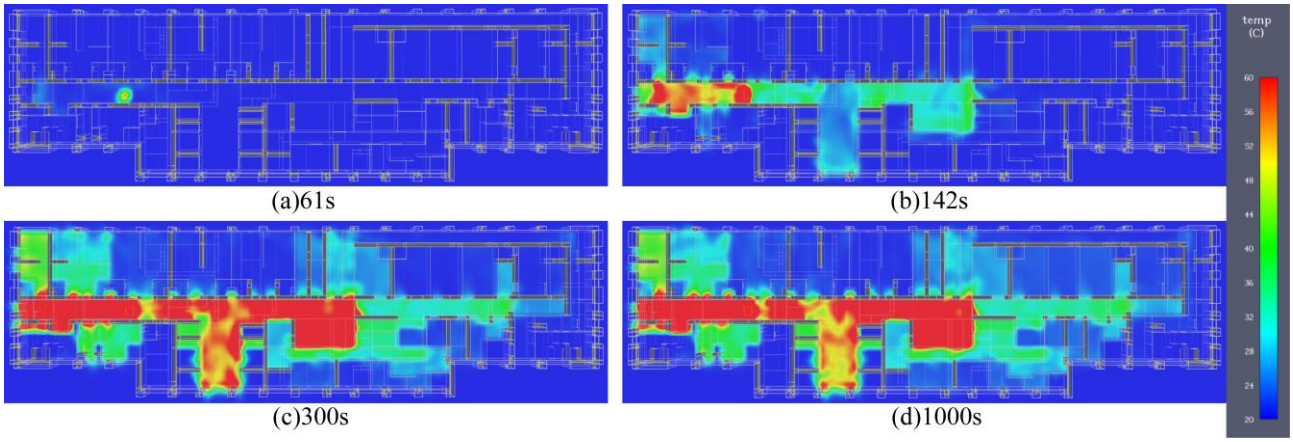


Fig. 9. Temperature field variation on the sixth floor under fire scenario B.

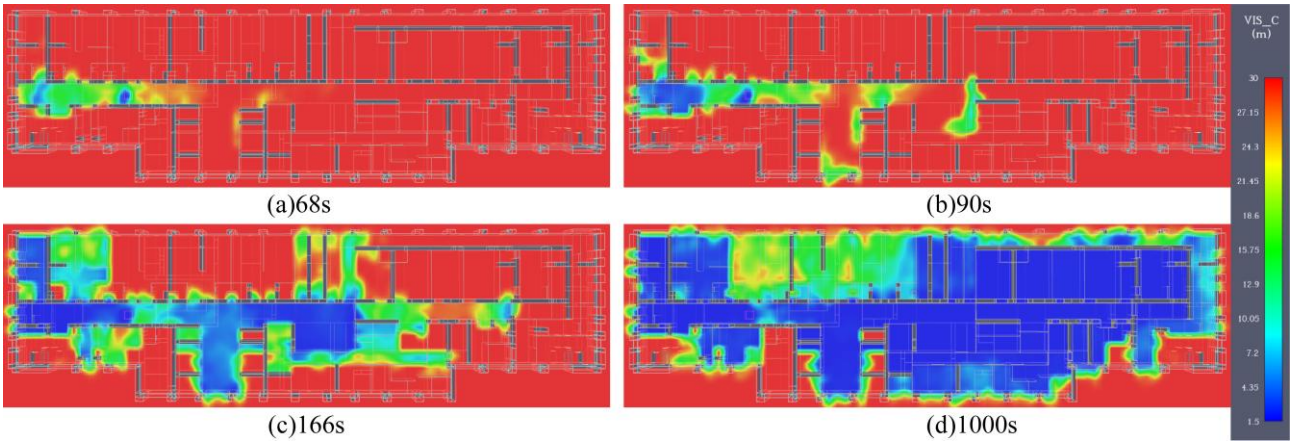


Fig. 10. Visibility variation on the sixth floor under fire scenario B.

3.1.3. Simulation Results of Fire Scenario C

In Scenario C, the fire source is located farther from the stairwells, causing smoke to rise more slowly than in Scenarios A and B, as shown in Fig. 11. In Scenarios A and B, CO concentrations exceed 500 ppm only at the fire source. However, in Scenario C, the relatively enclosed location of the fire source results in a larger area on the sixth floor experiencing CO concentrations above 500 ppm. As illustrated in Fig. 12, CO levels at the fire source exceed the human tolerance limit at 150 s, and with smoke dispersion, rooms near the fire source also reach CO concentrations of 500 ppm.

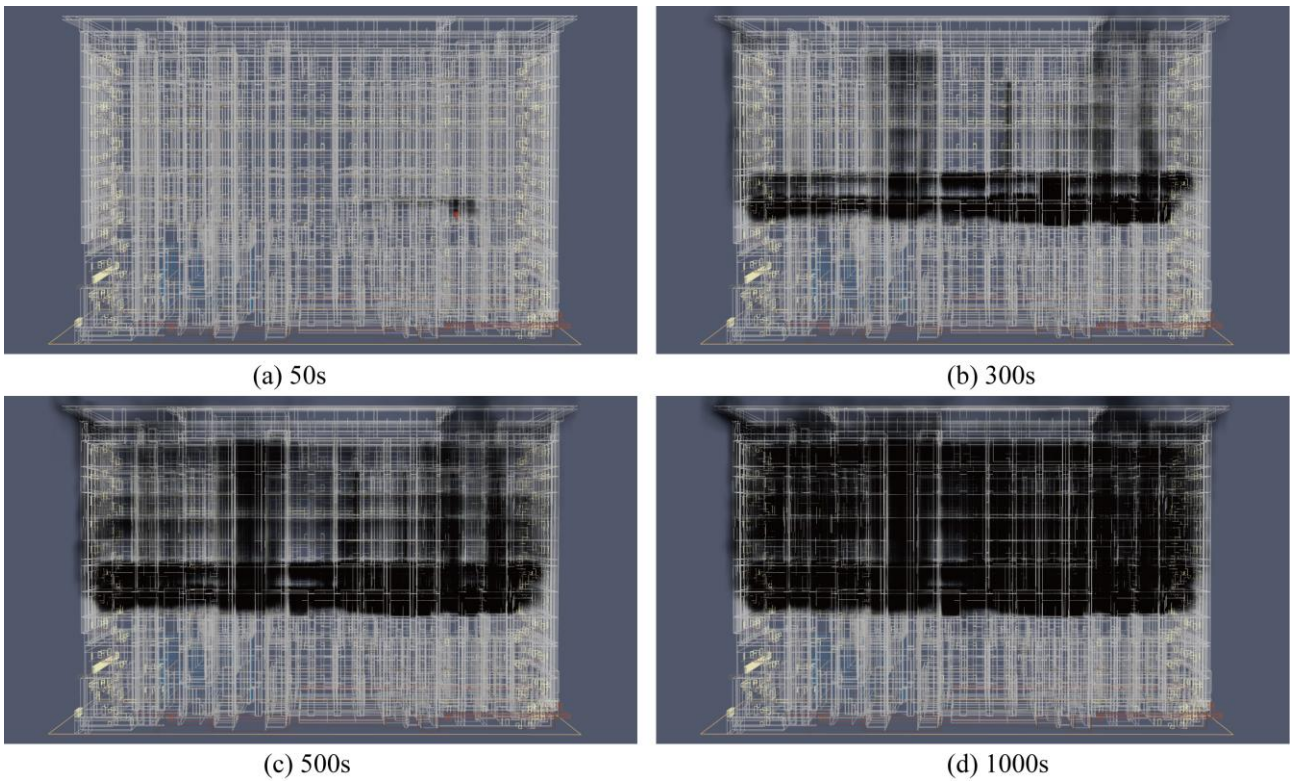


Fig. 11. Smoke evolution in fire scenario C.

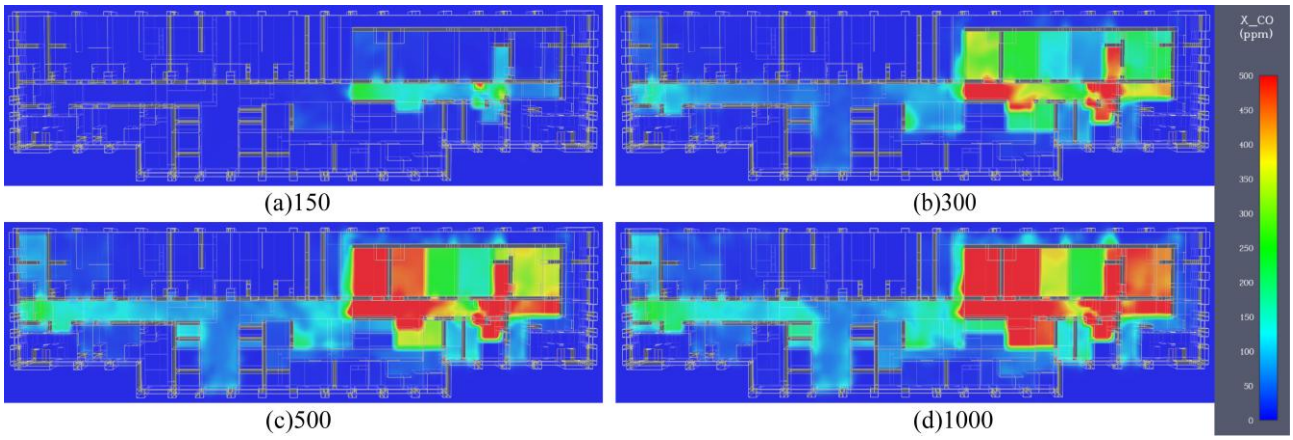


Fig. 12. CO concentration variation on the sixth floor under fire scenario C.

The temperature at the fire source reaches 60°C at 53 s. By 173 s, high temperatures have spread throughout the corridor near the fire source, but the elevated temperatures only affect Stair 2, leaving Stairwell 1 unaffected, as shown in Fig. 13.

Fig. 14 shows the visibility changes on the sixth floor for Scenario C. Visibility near the fire source drops below 5 m at 59 s, and by 270 s, visibility throughout the sixth-floor corridor falls below 5 m.

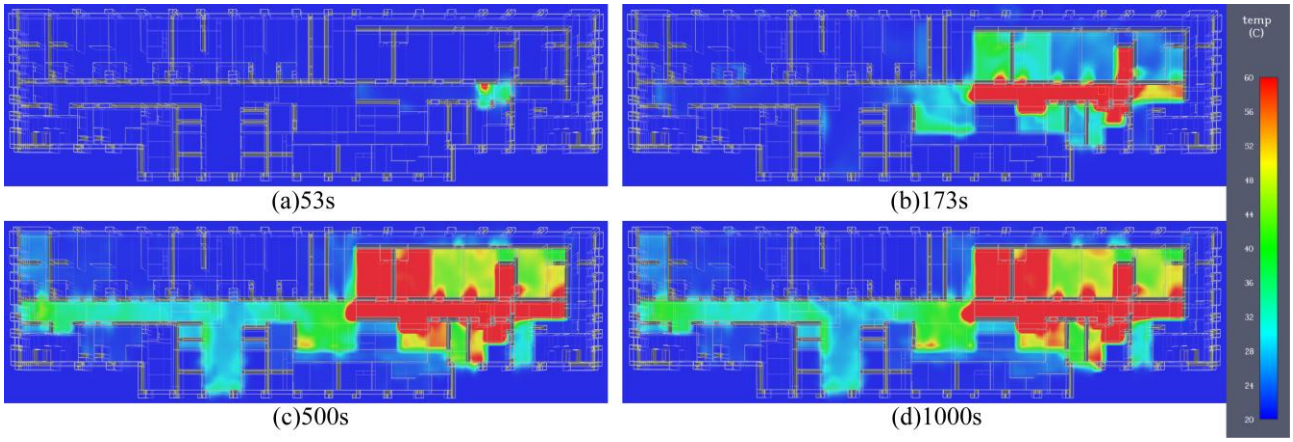


Fig. 13. Temperature field variation on the sixth floor under fire scenario C.

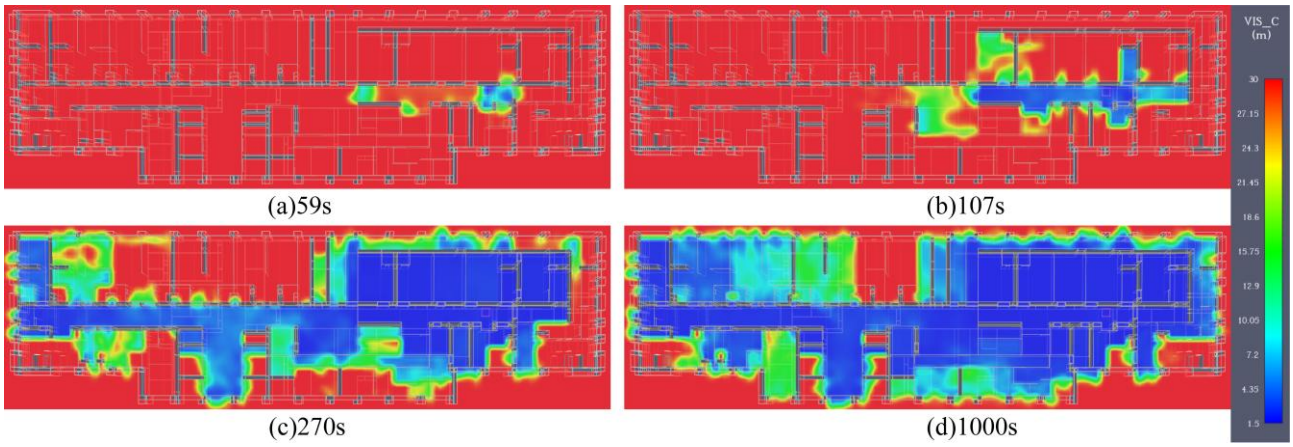


Fig. 14. Visibility variation on the sixth floor under fire scenario C.

3.1.4. Available Safe Egress Time

The smoke distribution across the three scenarios indicates that smoke does not spread below the sixth floor, and the fire primarily affects evacuation on the sixth floor and above. Since both stairwells are equipped with fire lobbies, smoke penetration into the stairwells is minimal, and the temperature, CO concentration, and visibility within the stairwells remain within human tolerance limits, as shown in Fig. 15, Fig. 16 and Fig. 17. Therefore, evacuees can be considered to have completed a safe evacuation upon entering the stairwells. Among the three scenarios, the most critical factor affecting evacuation is visibility, with the primary hazard concentrated on the sixth floor. Other floors also experience areas where visibility drops below 5 m, mainly around elevator shafts, which have negligible impact on evacuation. Table 9 presents the available safe evacuation times for the three scenarios, indicating the time windows during which evacuees can safely enter stairwells and move away from the fire source.

Table 9

Available safe egress time.

Fire Scenarios	near the fire source	Stairwell 1	Stairwell 2
Scenarios A	0s	70s	160s
Scenarios B	0s	40s	110s
Scenarios C	0s	145s	0s

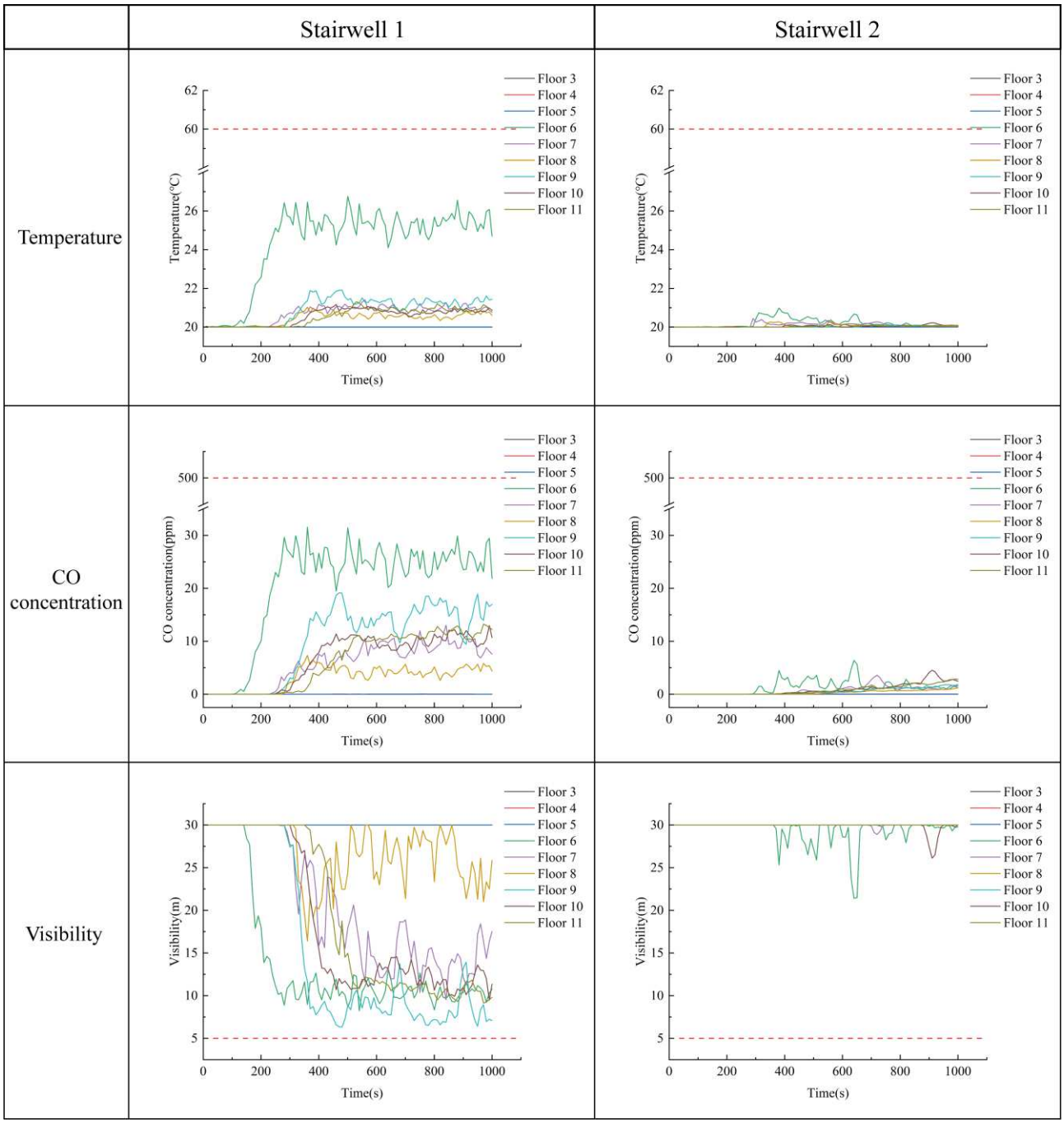


Fig. 15. Variations of temperature, CO concentration, and visibility in the stairwell under fire scenario A.

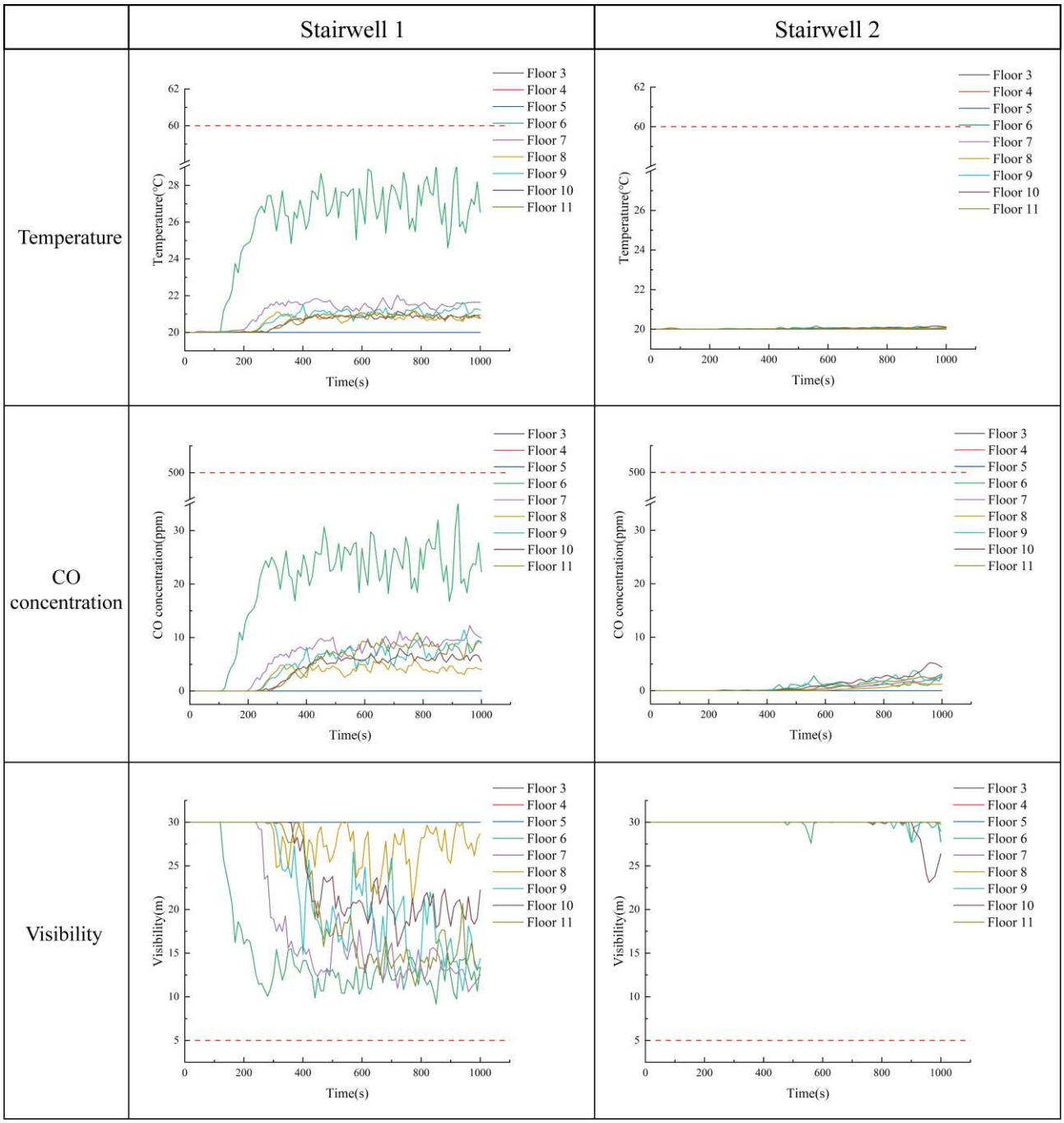


Fig. 16. Variations of temperature, CO concentration, and visibility in the stairwell under fire scenario B.

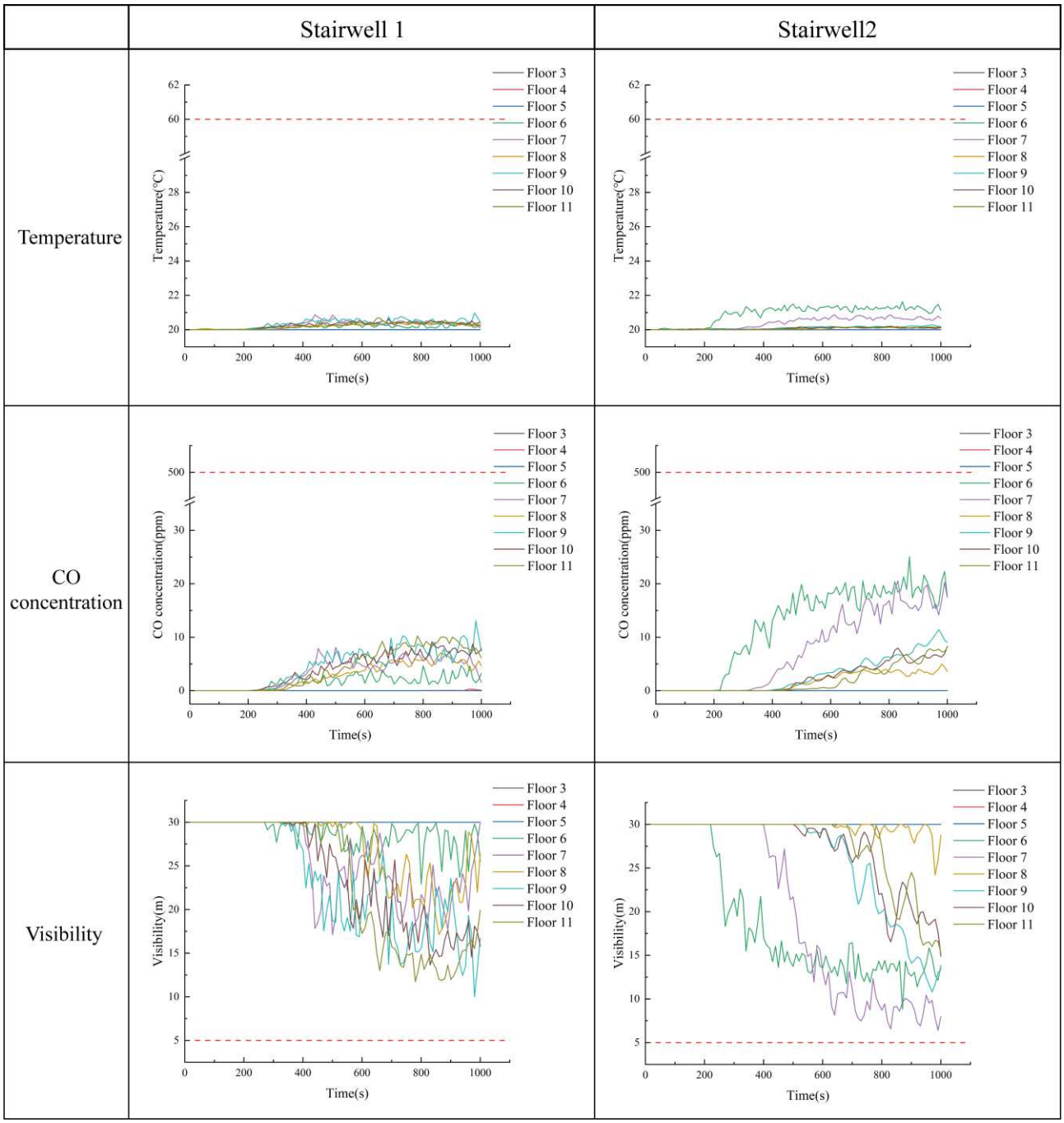


Fig. 17. Variations of temperature, CO concentration, and visibility in the stairwell under fire scenario C.

3.2. Analysis of Evacuation Results

3.2.1. Evacuation Efficiency Analysis

The evacuation times for S1–S4 are 986.9 s, 727.9 s, 897.5 s, and 667.5 s, respectively. The usage times of exits in S1 are summarized in Table 10. The hospital ward studied in this paper has three exits (Exit 01, Exit 02, and Exit 03). During the S1 evacuation, most occupants chose Exit 02, while only thirteen evacuees used Exit 03, as shown in Table 10. The total usage times for Exit 01 and Exit 03 were significantly lower than that of Exit 02, accounting for only 43.7% and 27.9% of the overall evacuation time, respectively.

Table 10

S1 exit utilisation rate.

Exit	First used/s	Finally used/s	Number of users
Exit01	22	453	161
Exit02	11	986.9	613
Exit03	25	300.1	13

During the evacuation in S2, the utilization of the two stairwells was more balanced, with no exits being underused. After adjusting the exit assignments, the usage times and number of evacuees passing through each exit are shown in Table 11. The effective usage times for Exit 01 and Exit 03 increased substantially compared with S1, with Exit 01 increasing by 40.8% and Exit 03 by 58%. The improvement in Exit 03 utilization was particularly pronounced: in S1, only thirteen evacuees used Exit 03, whereas in S2, the number increased to 102 after implementing designated exit assignments. Fig. 18(a) presents a comparison of average pedestrian flow between S1 and S2, showing the most significant improvement at Exit 01. In S2, Exit 01 was used exclusively by independently evacuating occupants who did not require assistance or additional space, resulting in faster flow. Moreover, 571 evacuees used Exit 01 in S2, an increase of 410 individuals compared with S1, representing a 2.5-fold rise in usage.

Table 11

S2 exit utilisation rate.

Exit	First used/s	Finally used/s	Number of users
Exit01	22	637.4	571

Exit02	46	727.9	114
Exit03	47	672.4	102

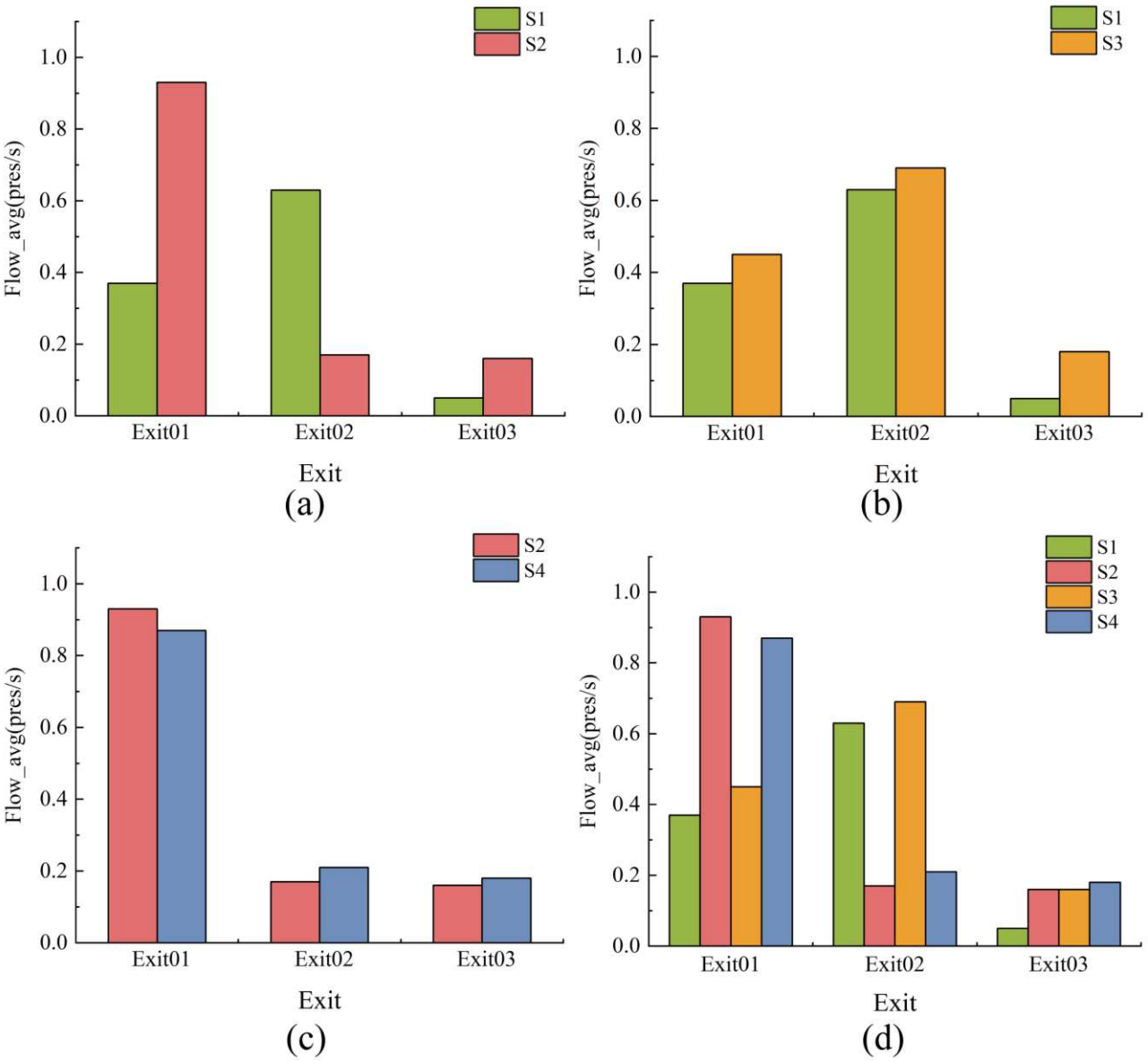


Fig. 18. Comparison of average pedestrian flow rates at exits under different scenarios.

The evacuation time for S3 was 897.5 s, representing a 9% reduction compared with S1. Table 12 summarizes the exit usage in S3. Compared with S1, the effective usage time of Exit 03 in S3 slightly decreased, but the number of evacuees increased by 30, resulting in the highest average flow rate. The average flow rates of the other two exits also increased, as shown in Fig. 18(b). However, compared with S2, S3 only implemented priority settings, and the imbalance in exit utilization persisted. Consequently, the evacuation time in S3 increased by 169.6 s relative to S2.

Table 12

S3 exit utilisation rate.

Exit	First used/s	Finally used/s	Number of users
Exit01	22	318.2	132
Exit02	11	897.5	612
Exit03	4725	288.3	43

The evacuation time for Scenario S4 was 667.5 s, which is 60 s shorter than that of S2, representing an 8.2% increase in evacuation speed. The usage of the three exits is summarized in Table 13. Similar to S2, exit assignments in S4 were fixed, resulting in the same number of evacuees per exit. As shown in Fig. 18(c), the average flow rates between S2 and S4 did not change significantly. Compared with S3, which only implemented priority settings, S4 demonstrated higher evacuation efficiency. By combining balanced exit usage with priority assignments, S4 outperformed the strategy that applied priority alone.

Table 13

S4 exit utilisation rate.

Exit	First used/s	Finally used/s	Number of users
Exit01	22	667.5	571
Exit02	48	646	114
Exit03	48	607.5	102

Bedridden and wheelchair-bound patients are the primary contributors to prolonged evacuation times. In this study, the refuge rooms added in Scenario S5 were insufficient to accommodate both types of patients; therefore, only bedridden patients were allowed to use the refuge rooms. Based on prior analyses, exit usage should be balanced during evacuation. Consequently, self-evacuating patients, caregivers, and medical staff were assigned separate evacuation paths.At this stage, wheelchair-bound patients are the slowest evacuees, and therefore were assigned to use Exit 02. Simulations of two evacuation scenarios for wheelchair patients using Exit 02 showed that the total evacuation times differed by only 10 s, and the difference in average flow rate at the exit was less than 0.02.The scenario with the shorter evacuation time was caregivers and medical staff using Exit 03, and self-evacuating patients used Exit 01, resulting in a total evacuation time of 427 s. This

configuration was designated as Scenario S5, with exit usage times summarized in Table 14. Among the first four scenarios, S4 had the shortest evacuation time, yet it was still longer than that of S5. In S5, bedridden patients were prevented from using the stairwells, which significantly reduced the overall evacuation time.

Table 14

S4 exit utilisation rate.

Exit	First used/s	Finally used/s	Number of users
Exit01	32.3	427	211
Exit02	37.4	409.2	105
Exit03	22.1	426	359

Fig. 19 presents the total evacuation times for the five scenarios. Analysis indicates that assigning different types of evacuees to specific exits (S2 and S4) not only improves the utilization of emergency exits but also reduces interference from bedridden patients on other evacuees, thereby enhancing evacuation efficiency and shortening total evacuation time. Although implementing priority settings can mitigate congestion, their impact on evacuation time is limited and, in some cases, may even increase the required evacuation duration. In summary, when refuge rooms are not available, the shortest evacuation time is achieved in S4; when refuge rooms are provided, S5 yields the most efficient evacuation.

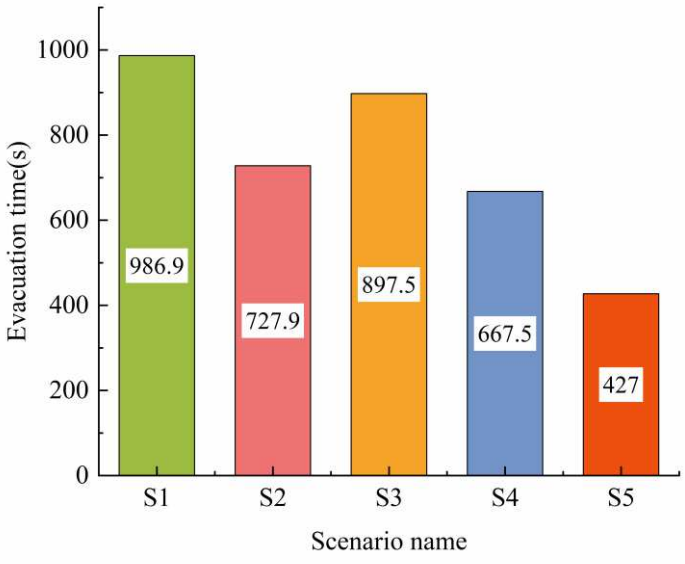


Fig. 19. Evacuation times in different scenarios.

3.2.2. Crowd Congestion Analysis

Figure 20 illustrates the time of initial congestion and the duration of congestion in stairwells across different floors for the four scenarios. Due to the building layout, the initial positions of evacuees were closer to Exit 02. Consequently, in S1 and S3, more evacuees chose to use Stairwell 2 and Exit 02 for evacuation. In S2 and S4, bedridden patients were assigned to Exit 02, primarily using Stairwell 2, which resulted in longer congestion durations between the third and sixth floors.

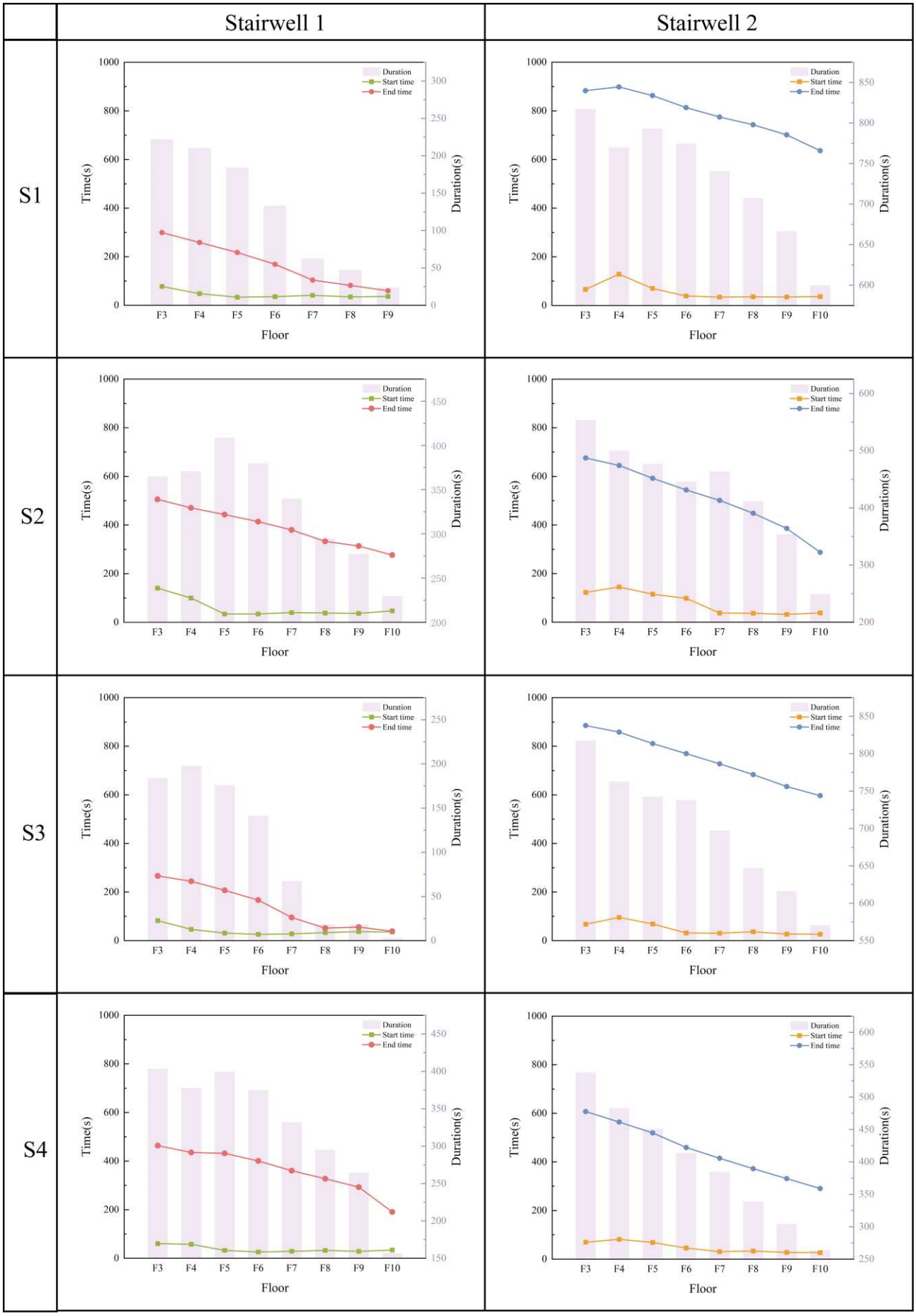


Fig. 20. Congestion duration at different floors in scenarios 1–4.

Comparison with S1 shows that the proportion of total evacuation time spent in congestion on Stairwell 1 increased in S2, due to the higher number of evacuees assigned to this stairwell after exit assignment. Although the number of users of Stairwell 2 decreased, most were bedridden patients, so the reduction in congestion duration was relatively limited. Fig. 21 illustrates the occupant density in Stairwell 2 at 300 s for S1 and S2. The figure shows that Staicase 2 in S1 had a significantly higher density than in S2, indicating more severe congestion. Fig. 22 illustrates the changes in the remaining number of occupants within the building for S1 and S2. The evacuation in S2 was smoother, with a stable evacuation rate, whereas in S1, the evacuation speed noticeably decreased after 300 s. Prior to 300 s, the evacuation rate in S1 was slightly faster than in S2. In S1, fewer evacuees used Stairwell 1, resulting in lower congestion and shorter congestion duration compared to S2, which allowed for a faster initial evacuation. However, after 300 s, evacuees concentrated in Stairwell 2, leading to increased congestion and even temporary stoppages, thereby reducing the overall evacuation speed.

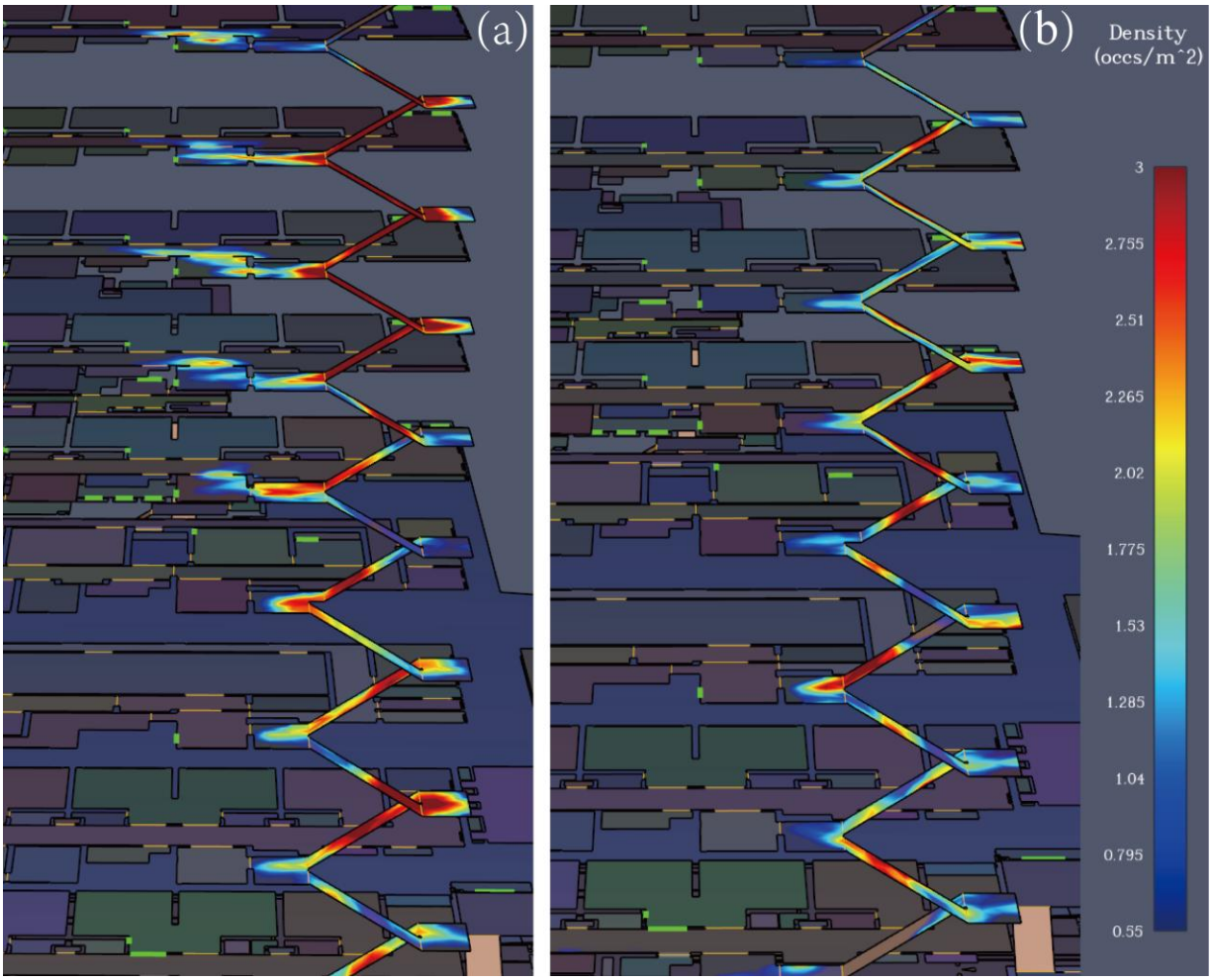


Fig. 21. Evacuation status of Stairwell 2 at 300 s. (a) S1, (b) S2.

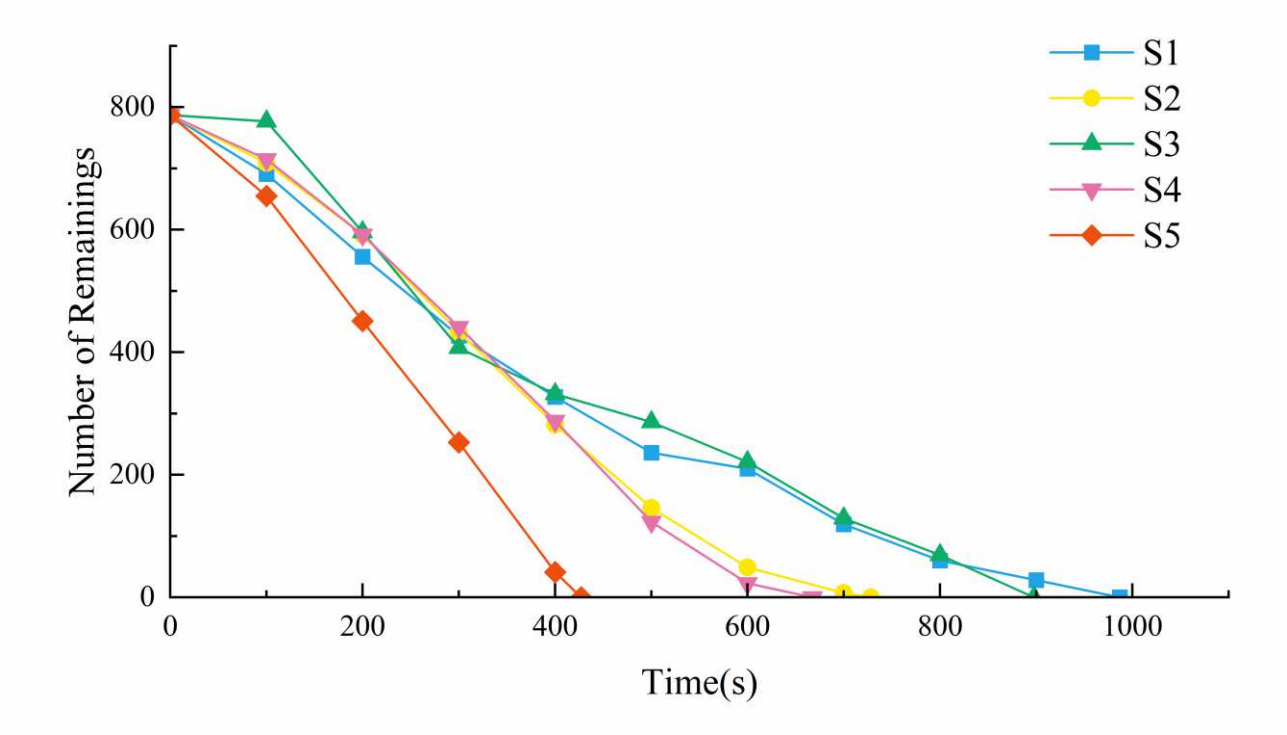


Fig. 22. Evacuation profiles of remaining occupants under different scenarios.

The remaining occupant curves for S1 and S3 are generally similar, as shown in Fig. 22. Prior to 802 s, evacuation in S1 was faster, with the majority of successfully evacuated individuals being self-evacuating occupants. In S3, self-evacuating occupants actively yielded to those requiring assistance, allowing assisted individuals to evacuate first. Consequently, fewer occupants were evacuated during this period. Once the majority of assisted patients had completed evacuation, the remaining self-evacuating occupants were able to evacuate at a higher speed. Consequently, after 802 s, the evacuation rate in S3 increased, resulting in a total evacuation time that was 89 s shorter than that of S1. Since S3 only implemented priority assignment, the underutilization of some exits was not alleviated. A large number of evacuees congested Stairwell 2, which significantly reduced evacuation efficiency. As a result, the total evacuation time in S3 was longer than in S2.

Comparison of occupant number trends between S2 and S4 is shown in Figure 22. Prior to 450 s, the two curves nearly overlapped, indicating similar evacuation rates. After 450 s, the advantage of priority assignment became apparent, with fewer remaining bedridden and wheelchair-bound patients in S4, resulting in faster subsequent evacuation. Between 540 s and 550 s, both scenarios exhibited a reduction in evacuation speed. During this period, the majority of remaining occupants were bedridden patients, whose slow mobility decreased the overall evacuation rate. The corresponding congestion duration is shown in Fig. 20.

Both priority-assigned scenarios, S3 and S4, exhibited a similar pattern: the initial evacuation rate was nearly identical to that of non-priority scenarios, while the late-stage evacuation rate was slightly faster. With priority assignment, bedridden and wheelchair-bound patients completed evacuation earlier. By the final stage, the majority of remaining occupants were self-evacuating individuals, who moved more quickly, resulting in a slightly higher evacuation rate at the end in the priority-assigned scenarios.

As shown in Figure 22, the evacuation curve for S5 was smoother than those of S1–S4. During the S5 evacuation, congestion in Stairwell 1 between floors 6 and 11 began at 40 s and gradually dissipated floor by floor by 150 s, disappearing completely by 303 s. In Stairwell 2, congestion occurred on all floors, starting at 36 s and lasting until 401.2 s. The introduction of refuge areas resulted in the main source of congestion being wheelchair-bound patients, who all evacuated via Stairwell 2 using Exit 02. Consequently, congestion in Stairwell 2 persisted longer, whereas Stairwell 1, with no wheelchair-bound patients, cleared more quickly.

Comparison of congestion across the five scenarios indicates that bottlenecks typically occurred in areas occupied by bedridden and wheelchair-bound patients. Their slower evacuation speeds made them more likely to impede other evacuees, particularly the bedridden patients who require more space. In S5, by avoiding the use of stairs for bedridden patients, the movement speeds of evacuees in both stairwells were more uniform. Although congestion still occurred, its impact on overall evacuation was minimal. In terms of both reducing total evacuation time and alleviating congestion, S5 performed best, followed by S4. These findings highlight the importance of providing refuge areas in hospital wards and balancing the utilization of different exits.

3.3. Optimal Evacuation Strategy

Under Fire Scenario A, patients on the sixth floor in S1 and S3 were unable to evacuate safely, whereas evacuees in S2, S4, and S5 were able to reach the stairwells within the available safe evacuation time. Therefore, under Fire Scenario A, when refuge areas are provided within the building, the S5 strategy is the most effective; in the absence of refuge areas, the strategy implemented in S4 is recommended.

Under Fire Scenario B, evacuees needed to move away from the fire source within 61 s and reach Stairwell 1 within 90 s. Among the five evacuation scenarios, S5 enabled the fastest clearance of the danger zone, taking 38 s, followed by S4 at 43 s. Given that the evacuation response time is 60 s, none of the strategies allowed evacuees to complete the evacuation within the available safe time. The fire originated between the entrance of Stairwell 1 and the refuge area, making it impossible to avoid the hazard by intervening in evacuees' route choices. Therefore, reducing the evacuation response time was considered. When the response time was shortened to 23 s, S5 enabled a safe evacuation, whereas S4 required a response time reduction to 18 s to achieve the same. Based on the results of Fire Scenario B, particular attention should be paid to preventing fires at the entrances of stairwells and refuge areas. In the event of a fire, priority should be given to evacuating individuals located near the fire source.

In Fire Scenario C, the primary hazard was located outside Stairwell 2, an area without patient rooms. Some self-evacuating individuals used this route, and the last evacuee required 76.5 s to leave the area, clearly preventing a safe evacuation. Since it is possible to avoid passing by the fire source in this scenario, the entrance to Stairwell 2 on the sixth floor should be closed during the fire, and evacuees on the sixth floor should use Stairwell 1. After modifying the evacuees' route choices based on S5, the total evacuation time was 449.8 s; based on S4, it was 647 s. Following these modifications, all individuals in both scenarios were able to evacuate safely.

4. Conclusion

This study investigated fire evacuation strategies for a hospital inpatient ward by integrating fire dynamics simulation and evacuation modeling. PyroSim was used to simulate fire scenarios and determine the Available Safe Egress Time ($ASET$), while Pathfinder was employed to analyze the evacuation process and calculate the Required Safe Egress Time ($RSET$). By comparing multiple evacuation strategies, the optimal approach was identified.

The results indicate that visibility is the most critical factor affecting evacuation safety in all fire scenarios. Proper allocation of exits can significantly improve exit utilization, reduce congestion, and enhance evacuation efficiency. Although priority-based strategies can somewhat alleviate obstruction, their impact on total evacuation time is limited. In contrast, the provision of

refuge rooms effectively prevents bedridden patients from using stairways, substantially reducing congestion and markedly shortening evacuation time.

Evacuation strategies and emergency plans should be tailored to the specific fire location. In the present study, the primary challenge in fire scenario A was congestion within the stairwells. Therefore, the strategy incorporating refuge rooms (S5) was identified as the most effective, followed by S4. When the fire originates near stairwell entrances, as in scenarios B and C of this study, the main challenge is that the proximity of the fire to the exits causes the exits to become hazardous earlier. By adjusting the evacuation response time and controlling access to the stairwells based on the S5 and S4 strategies, occupants can evacuate safely within the available safe time or avoid the hazardous areas altogether. The combination of optimized exit allocation and well-designed refuge areas provides the most effective evacuation strategy for high-rise hospital wards, significantly reducing evacuation time and enhancing occupant safety during fire emergencies.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Peixu Zhang: Conceived, designed, Writing-review & editing, Supervision, Funding acquisition. **Siqi Liu**: Writing-original draft, Original draft preparation, validation, Methodology. **Xiaolu Wang**: Conceptualization and Methodology. **Yanru Bao**: Formal analysis, Data curation, Conceptualization. **Yunling Gao**: Supervision, Project administration. **Yanan Chen**: Investigation, Formal analysis. **Jiquan Zhang**:Investigation, Formal analysis.

Reference

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