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Modeling of Safe Evacuation Conditions at the Construction Site for Building Type "I"

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Abstract: To ensure the safety of construction site personnel and to improve the efficiency of emergency safety evacuation of site personnel, this study analyzes the risk reasons for fire accidents and the characteristics of combustion fires on construction sites. Based on a refined BIM model, a numerical simulation of the fire situation is performed using PyroSim (2019 version) software on a construction site. In the Pyrosim fire simulation model, fire scenarios with distinct construction stages and fire source locations are set up to simulate, compare, and analyze the varying pattern of each fire product in various fire scenarios. Using this information with the Pathfinder (2019 version) simulation model, a coupled simulation test of fire evacuation is conducted to assess the safety of evacuating individuals in each fire scenario. The results show that flammable materials in open spaces are more risky to burn than in confined spaces. After optimizing the utilization of safety exits and the density of people in the second simulation, it was found that the required safety evacuation time was reduced to 267 s, which is lower than the available safety evacuation time of 318.5 s for each scenario. All fire scenarios meet the safe evacuation criteria. The study results can provide a theoretical basis for developing fire response strategies for construction units and contribute to site safety management.

Keywords: BIM; construction site; coupled simulation; emergency evacuation; fire; numerical simulation

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1. Introduction

With 51,840,200 people employed in the construction industry in 2022, China's construction industry has more employees than other industries, and construction site safety accidents are frequent [1]. Among construction site safety accidents, fire accidents cause more significant economic losses; deaths are relatively high. China's firefighting yearbook [2] shows a substantial increase in fires on construction sites in China since 2017. With 2682 fires on construction sites in China in 2020, they are accounting for 15.8% of the total deaths and 45.9% of the real property damage. For example, in April 2023, 29 people died and 39 were injured in a fire at a hospital in Beijing caused by sparks from internal construction work. In March 2022, a fire at a construction site in Jiangsu Province resulted in seven deaths, four injuries, and a direct economic loss of RMB 10,607,200. A fire at a construction site in Sejong, South Korea, in June 2018 killed 40 people. In August 2010, a fire caused by illegal welding work during renovation works in a Shanghai flat caused 58 deaths, 71 injuries, and a direct economic loss of RMB 158 million. As a result, there is a need to assess the fire risk on building sites as well as research the development and spread of fire on construction sites. This study's findings will be used to establish scientific and reasonable fire prevention measures, increase the efficiency of evacuation of people during fires, and reduce human-influenced casualties and property damage.

At present, research on fire safety management at construction sites mainly focuses on fire warning; Wang and Yang et al. [3,4] developed an intelligent site fire warning system and a BIM-based construction site fire safety management system using information technology tools. Yang et al. [5] developed a real-time construction site fire detection system by collecting and processing construction site CCTV screen data. Liu et al. [6] constructed a fire hazard tracking system, and the study proposed a method for evaluating fire hazards on construction sites. Mohamed et al. [7] used a combination of BIM and computer simulation to form a visual framework that predicts the time for labor evacuation under various conditions on the construction site and uses this simulated time to develop and evaluate evacuation plans. Existing research has focused more on fire warning and assessing fire risk, using less simulation to obtain intuitive experimental data [8–10]. However, simulation allows visual analysis of the changes in the various fire products following a fire and dynamic observation of the Motion rule of evacuees under fire conditions. It has a certain degree of scientific validity.

Numerical simulation using simulation software is one of the most prominent research methods for fire risk assessment [11–17]. Xiao et al. [18] used Pyrosim software and Pathfinder software to visualize and analyze the fire and evacuation of personnel from a prefabricated construction site to improve the efficiency of the safe evacuation of construction personnel after a fire during construction. Ekaterina Kirik et al. [19] developed an evacuation plan for the Winter Palace of the State Hermitage Museum by considering the development of a fire and the safety of evacuation of people through a simulation. Zou et al. [20] proposed fire safety management measures by simulating and studying the smoke dispersion and evacuation of people in a dormitory building fire. Most of the fire risk assessment studies have been conducted between high-rise buildings [21–25], hospitals [25–29], schools [30,31], shopping malls [32,33], and nursing homes [34,35]. Due to the nature of buildings under construction, the fire risk differs greatly from most existing buildings. In recent years, construction sites have been subject to long construction cycles, labor-intensive production, restricted construction site areas, and disorderly stacking of flammable and combustible materials for multiple reasons, resulting in frequent fire safety accidents and severe casualties. To ensure the safe construction of building projects and the safety of construction personnel, in-depth research of the law of combustion products at various phases of construction and the evacuation of people under fire conditions is required.

Therefore, this paper builds a fire simulation model and a personnel evacuation simulation model based on a refined BIM model, using PyroSim and Pathfinder software, to analyze the variability of fire products under different construction stages and fire source locations and to assess the impact of smoke on personnel evacuation, using a building under construction as a background. The evacuation test can obtain the movement parameters of people during the evacuation, analyze the movement pattern of people, reasonably arrange the corresponding facilities of the building and improve the evacuation capacity of people. The test results can provide a theoretical basis and technical support for preventing fires on construction sites and evacuating people under construction site fire conditions.

Fire smoke and high-temperature heat plumes are the top fire products. The physiological motor ability and psychological state of personnel can be affected by the products of fire, which can lead to misjudgments during the evacuation process. The specific hazards of fire products are as follows:

High-temperature heat plume; the high-temperature heat plume mainly affects the circulatory and nervous systems of the body. Fire fumes are generally of a high temperature. The high temperature of fire smoke can have an adverse effect on people and objects. In addition to causing a person to have a dry mouth and feeble limbs, prolonged exposure to high temperatures can endanger a person's life [36]. The extent to which temperature affects the human body is shown in Table 1.

Toxicity of the smoke; when a fire breaks out, large amounts of CO and CO_2 are released, as well as large amounts of nitrogen, styrene, and other toxic substances. Of these, CO is the most critical substance causing human casualties. This is mainly since hemoglobin in human blood binds CO more strongly than O_2, which leads to a decrease in the level of O_2 in the blood and a lack of oxygen supply, eventually leading to death [37]. The extent of the effects of different volumes of CO on humans is shown in Table 2.

Shading of smoke; combustible materials produce large quantities of solid particulate matter and other gas phase products and accompanying liquid droplets during combustion, which are collectively referred to as flue gas. The build-up of smoke can lead to reduced visibility, affecting the range of human vision and hurting people's evacuation. The SFPF Handbook of Fire Engineering indicates that if there is a fire, based on the building's layout and the psychological behavior of the personnel, the visibility needed for safe egress is 13 m. The Australian Guide for Fire Engineers sets a reference value of 10 m for visibility in large-space environments and 5 m for small spaces [38].

The human tolerance limit factors can be measured in terms of smoke visibility, temperature, and CO concentration, and the critical values of these three parameters are analyzed to determine whether a fire hazard state has been reached [39,40]. The threshold values for each parameter to reach a hazardous state are shown in Table 3.

Table 1. Limit of human body tolerance to hot air.

Ambient Temperature/°C	Humidity	Time of Human Endurance/min
<60	Well-hydrated	>30
60	Moisture content < 1%	12
100	Moisture content < 1%	1

Table 2. Degree of harm to the human body of different CO concentrations.

ϕ(CO)/%	Degree of Hazard
0.01	Little effect on the human body for a few hours
0.05	Little impact on the human body within one h
0.1	Headache, discomfort, and vomiting after one h
0.5	Causes severe headache, life-threatening after about 20–30 min
1.0	Loss of consciousness after several breaths, possible death after 1–2 min

Table 3. Range of factors reaching risk status.

Human Tolerance Limit Factors	Hazard Threshold
CO concentration (%)	0.04
Temperature (°C)	60
Visibility (m)	10

2. Fire Simulation Analysis

2.1. Building Overview

Taking a student dormitory building under construction at a university as the object of study, a BIM model was established through Revit (2016 version) software, as shown in Figure 1. The dormitory building under construction is of an "I" shape and consists of four dormitory blocks and a corridor, of which the four blocks share a common hall. The total construction area is 24,000 square meters, and the building height is 22.5 m.

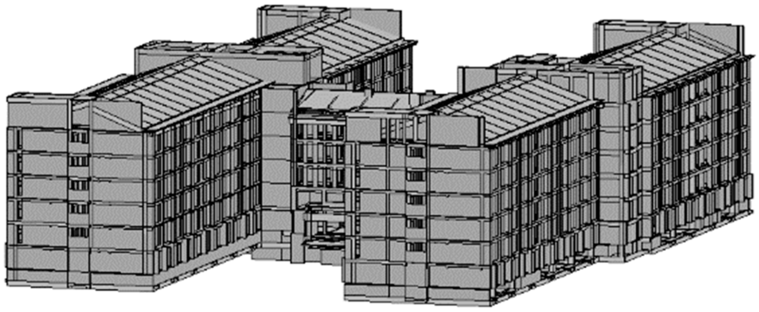


Figure 1. BIM model of a dormitory building under construction.

2.2. Fire Simulation Model Construction

2.2.1. PyroSim Model Building

The BIM model is the basis for the lightweight process, removing components such as PHC piles that do not affect the simulation results. Import the lightened BIM model into PyroSim software and add surface properties and defined reactions to form the PyroSim model. On the first and second floors are pick an empty hall, and above the third floor, the connecting corridor consists of a corridor and rooms together, which are narrow. Therefore, the principle of least favorability was considered, and the combustible material was placed in the connecting corridor of the third floor. The fire source is set on the combustible surface, and the burning area is 1 m $\times$ 1 m. CO concentration, temperature, and visibility detectors are installed at each safety exit and in the middle area of the corridor. A1, A2, B1, B2 are monitoring points for safety exits; A1-1, A2-1, B1-1, B2-1 are monitoring points at the corridors; and A4, B4 are monitoring points at the two stairwells connecting the corridors in the A and B areas. The building is zoned and divided into Area A, Area B, and the corridor, as shown in Figure 2.

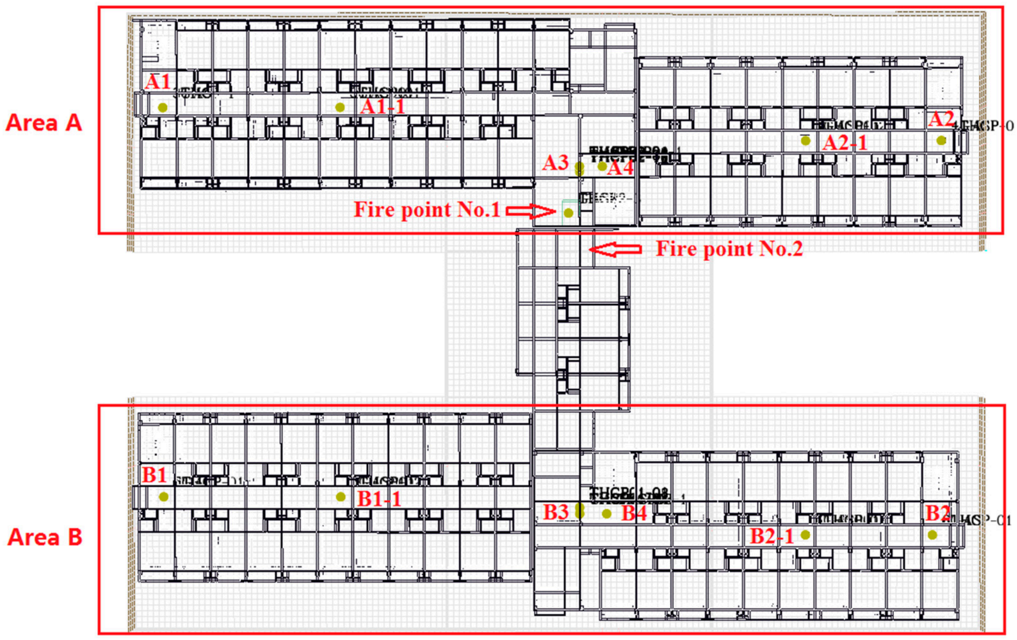


Figure 2. Location map of all combustibles and detectors.

According to Shi et al. [41] and "The Technical Standard for Building Smoke Prevention and Exhaust System" [42], the critical safe smoke height at the fire scene can be calculated using Equation (1).

$$H_s = H_b + 0.1H \quad (1)$$

where: H_s is the critical safe smoke height (m); H_b is the average height of the crowd at the fire scene (m); H is the height of the space where the fire occurred (m).

Calculate the average height of the simulated people H_s = 1.652 m. The average height of this simulated building is 3.0 m, the critical safe smoke height $H_s = 1.652 + 0.1 \times 3.0 = 1.952$ m, so consider setting each slice and detector to a height of 2 m above the ground.

According to the FDS guidebook, the fire source feature diameter determines the grid size. Set the grid size between D*/16 and D*/4 and the fire source feature diameter is given by Equation (2) [43].

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

where: $D*$ is the characteristic diameter of the fire source, m; Q is the rate of heat release from the fire source, kw; ρ_∞ is the air density, 1.2 $\mathrm{kg/m^3}$; c_p is the specific heat capacity of air, 1.014 $\mathrm{kJ/kg \cdot K}$; T_∞ is the room temperature at the time of the fire, 20 °C (293 K), K; g is the acceleration of gravity, 9.8 $\mathrm{m/s^2}$. According to Equation (1), the grid size was set to 0.5 m × 0.5 m × 0.5 m, taking into account the computer performance.

The subject of this thesis is the construction site. Therefore, it is assumed the model has no smoke and sprinkler system, no windows or doors are installed, and the fire partition is not effectively divided.

2.2.2. Multiple Fire Scenario Design

This paper uses a non-stationary model $Q = \alpha t^2$ to determine the heat release rate to make the fire simulation more accurate [44]. α is the fire growth factor, and t is the fire development time. Multiple fire scenarios are designed by calculating different scenarios' fire growth factor and maximum heat release rate. The fire growth factor is related to the fire burden on the building's internal walls and the interior finish rating, and can be calculated with the help of Equation (3):

$$\alpha = \alpha_m + \alpha_f \tag{3}$$

where: α_m is the effect of finishing materials on the interior walls and ceiling of the building on the fire growth coefficient. Considering the study is for a building under construction, so α_m is taken as 0.0035$\mathrm{kW/s^2}$. α_f is the influence of fire load density on fire growth coefficient, which can be determined using Equation (4).

$$\alpha_f = 2.6 \times 10^{-6} q^{5/3} \tag{4}$$

where: q is the fire load density, which is the ratio of the heat released by the complete combustion of all combustible materials in the room to the characteristic reference area of the room [45]. This can be determined using Equation (5).

$$q = \frac{\sum m_c H_c}{A_f} \tag{5}$$

where: m_c is the total mass of combustible material; H_c is the effective calorific value of combustible material; A_f is the total floor area in the space.

The fire reaches its maximum heat release rate when it ignites from the initial growth stage to the fully developed stage Q_c. The British scholar Thomas obtained an improved mathematical model based on a combination of previous studies [46], as shown in Equation (6):

$$Q_c = 7.8 A_f + 378 A \sqrt{H} \tag{6}$$

where: Q_c is the maximum heat release rate; A_f is the total surface area of the room after deducting the openings; A is the area of the openings; H is the height of the openings.

According to the statistics of China's firefighting yearbook, 95 typical cases of construction site fires were selected for study and analysis, and the statistical chart of specific fire causes is shown in Figure 3. Production fire operations and electrical fires were found to be the largest source of fire initiation, at 47.37% and 34.74%, respectively. Sparks from fireworks during construction can ignite materials, leading to fires [47]. A statistical analysis of the number of fires occurring at different construction stages at the construction site showed the most significant proportion of fires happened at the main and decoration stages, 42.86%, and 47.62%, respectively. This is because there will be a large amount of wooden formwork and sawn material at the construction site during the main construction phase. During the decoration phase, there will be a large amount of insulation and decoration material, which is a greater fire hazard. Considering that the main construction and decoration stages are the main stages of fire occurrence, this paper chooses these two stages as the simulation stages.

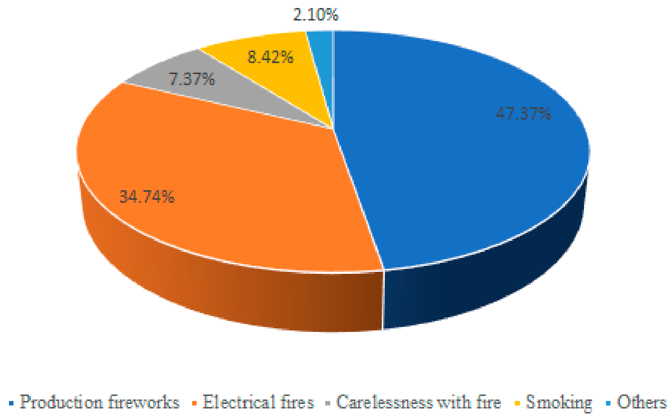


Figure 3. 95 Statistical chart of causes of construction site fires.

Therefore, a 3 m × 2 m × 2 m, 28 Kg/m^3 density of insulation and decoration material was selected to be stored in an open area next to the stairwell during the decoration and renovation phase for a simulation test. Then:

According to Equations (2)–(4) $\alpha = 0.0333 kW/s^2$; $Q_c = 10.93 MW$.

The main construction phase model sets up the interior surrounded by formwork wood material with a density of $550 Kg/m^3$, formwork thickness d of 0.02 m, then:

Calculated from Equations (2)–(4) to give $\alpha = 0.1512 kW/s^2$; $Q_c = 6.5 MW$.

As the location of the fire source is different between Scenario 1 and Scenario 2, this paper selects the case of decorative materials stored indoors for comparative fire numerical simulation analysis to ensure the rigor of the simulation test. Calculated from Equations (1)–(4), we get $\alpha = 0.1359 kW/s^2$; $Q_c = 6.5 MW$.

Based on these results, the fire scenarios are set up as shown in Table 4.

Table 4. Fire scenario design sheet.

Fire Scenario	Construction Stage	Location of Combustibles	Name of Fire Source Location and Type of Combustible Material	Fire Source Parameters
1	Decoration stage	Fire point No. 1	Open area on the third floor connecting corridor Combustibles: Thermal insulation decoration materials	$\alpha = 0.0333 kW/s^2$ $Q_c = 10.93 MW$
2	Main structure phase	Fire point No. 2	Inside the third-floor room of connecting corridor Combustibles: formwork (wood)	$\alpha = 0.1512 kW/s^2$ $Q_c = 6.5 MW$
3	Decoration stage	Fire point No.2	In a room on the side of the third floor connecting corridor, Combustibles: Thermal insulation decoration materials	$\alpha = 0.1359 kW/s^2$ $Q_c = 6.5 MW$

2.3. Analysis of Fire Products

2.3.1. Temperature Simulation Analysis

Figure 4 compares the temperature variation of each scenario at a height of 2 m above the ignition level at different times. The peak temperature and heat spread area in Scenario 1 is greater than in Scenarios 2 and 3. There are no significant differences between the temperature slices of Scenario 2 and Scenario 3, with temperatures concentrated at the connecting corridor and a small increase at the corridor. By the 200 s, the temperature at both Scenario 2 and Scenario 3 connecting corridors had risen above the critical level, and both exit A3 and B3 were not conducive to the safe evacuation of people. In Scenario 1, the heat diffuses into area A, and the temperature at A3 has risen above the critical value. From the 200 s to 400 s, in Scenario 1, the heat gradually spreads towards the corridors on both sides of Area A. In Scenarios 2 and 3, the heat spreads outwards from the corridors, but to a lesser extent. After 400 s, the temperature change in the three Scenarios stabilized and reached dynamic equilibrium. By the 600 s, no significant differences were seen in the temperature-slicing clouds for each Scenario compared to the 400 s.

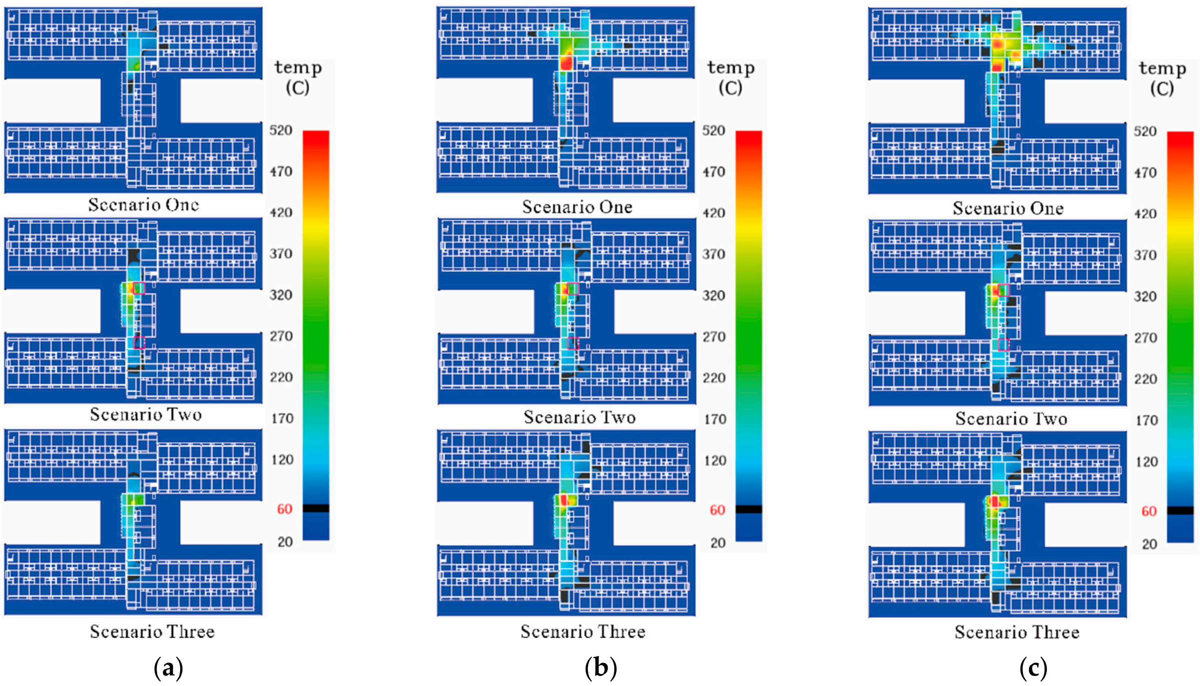


Figure 4. Temperature slices of the ignition layer at different moments in time for different scenarios. (**a**) t = 200 s. (**b**) t = 400 s. (**c**) t = 600 s.

2.3.2. Analysis of CO Concentrations

The variation of CO concentration at 2 m above the fire level for each scenario at different times is shown in Figure 5. According to simulation results, the CO yield in Scenario 2 is lower than in Scenarios 1 and 3, and the diffusion area of high CO concentration in Scenario 1 is larger than in Scenario 3. During the simulation time of 600 s, none of the areas in Scenario 2 reached the hazard threshold. By the 200 s of the simulation, the CO concentrations in the corridors of both Scenario 1 and Scenario 3 had risen above the critical values. By 400 s, the CO diffuses more towards the A area and less towards the corridor in Scenario 1, and the CO concentration at the corridor is already above the critical value in Scenario 3. By 600 s, most of the area at the corridor on either side of Area A in Scenario 1 has CO concentrations above the critical value. The CO concentration slice plots for Scenario 2 and Scenario 3 do not change significantly from the 400 s.

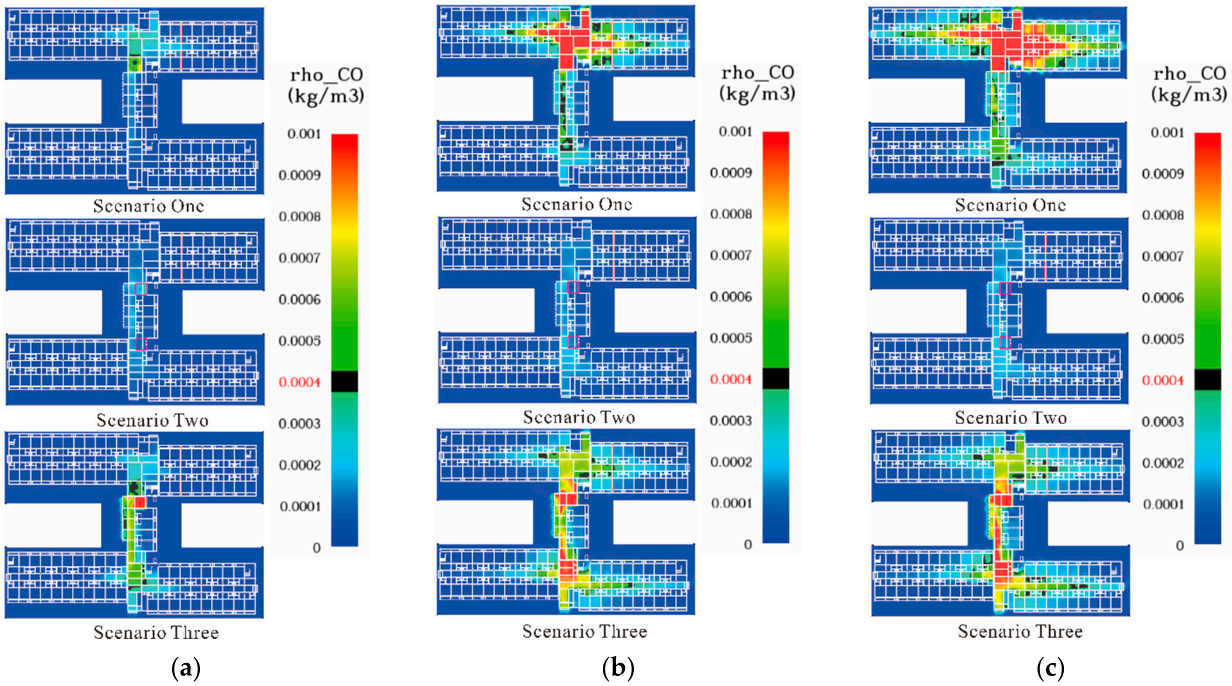


Figure 5. Slices of CO concentration at different moments in the ignition layer for different scenarios. (**a**) t = 200 s. (**b**) t = 400 s. (**c**) t = 600 s.

2.3.3. Visibility Analysis

Visibility is an important indicator of how people can escape from the scenario, and high smoke concentrations can block the view of escapees. Visibility monitoring slices were set at 2 m above the fire level for each scenario. The sections were taken at 100 s, 300 s, and 600 s, as shown in Figure 6. At 100 s, the smoke has been generated in Scenario 1, spreading towards the corridor in Area A. In Scenarios 2 and 3, the smoke spreads towards the corridor, reducing visibility below 10 m. By 300 s, visibility drops below 10 m at the corridors on either side of Area A in Scenario 1. The smoke diffusion rate into the left-hand corridor is higher than the right-hand side in both Scenarios 2 and 3, Areas A and B. Visibility at the left-hand corridor drops to below 10 m. By 600 s, the smoke had spread sufficiently, and visibility was low in all areas of the fire floor so that all safety exits could not be safely evacuated.

Second, dynamic detection by smoke dispersion revealed that smoke spreads upwards and at a high rate. For more accurate quantitative analysis, taking Scenario 1 as an example, smoke-sensing couples A4 and B4 are set respectively in the stairwell on both sides of the corridor on floors one to six. The height of each electric couple from the ground is 2 m, and their vertical coordinates are z = 2.0 m, z = 5.1 m, z = 8.2 m, z = 11.3 m, z = 14.4 m, and z = 17.5 m, respectively. Figure 7 shows a comparison of the results of the data output for each electric couple. Analysis shows the visibility of floors below the fire source layer is maintained at 30 m, and the vertical evacuation of personnel will not be affected. However, visibility at all floors above the fire source level dropped below 10 m during the simulation time. This is due to the smoke spreading upwards through the unenclosed stairwell, creating a chimney effect where the smoke fills the entire stairwell quickly, and visibility drops to dangerous distances. Therefore, the reduced visibility due to smoke diffusion greatly impacts the evacuation of people on the upper floors.

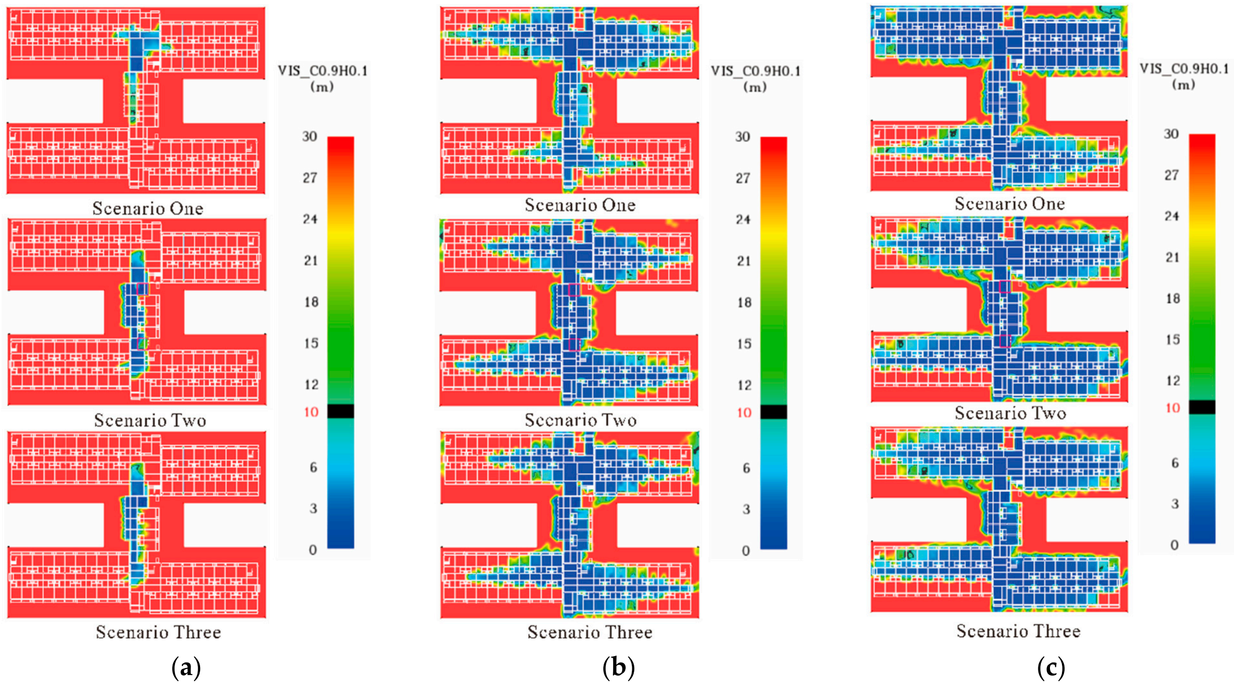


Figure 6. Visibility slices at 2 m for different scenarios. (**a**) t = 100 s. (**b**) t = 300 s. (**c**) t = 600 s.

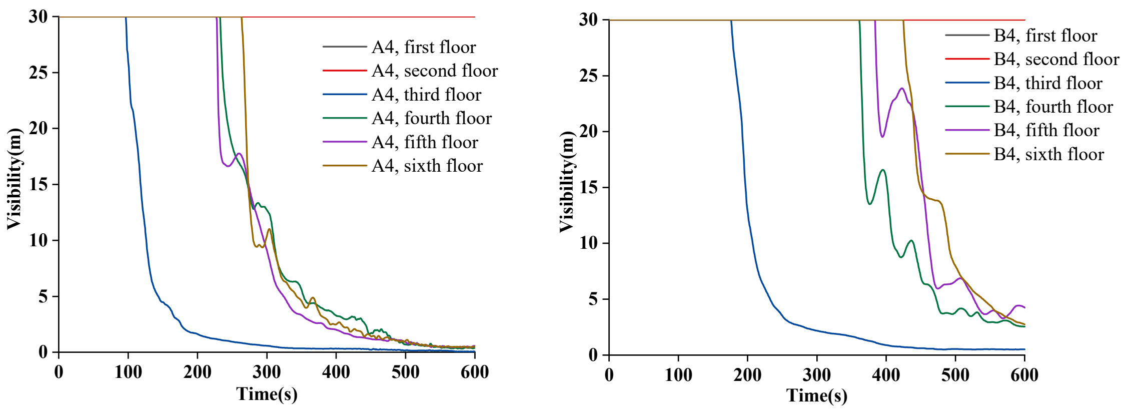


Figure 7. Variation of visibility at the vertical detection point in the stairwell.

Figure 8 shows a graph of visibility at each scenario corridor as a function of time. Analysis of Figure 8 shows that visibility threshold A1-1 in Scenario 1 is reached at 183 s, and people cannot be safely evacuated. A2-1, B1-1 and B2-1 reached critical values at 161 s, 444 s and 350 s, respectively. Scenario 2 is A1-1 (245 s), A2-1 (211 s), B1-1 (204 s), B2-1 (232 s). Scenario 3 is A1-1 (266 s), A2-1 (233 s), B1-1 (224 s), B2-1 (210 s).

In order to conduct an accurate and quantitative analysis of the visibility of the fire source layer, Figure 9 shows the curves of visibility changes over time at each safety exit in three different scenarios. The dotted line is the visibility threshold of 10 m, the dashed box is the local zoom area, and A, B, C, D, and E are coordinates where the visibility of each safety exit reaches the critical value under different scenarios. As seen from the coordinates of the critical values in Figure 9, the visibility at each measurement point drops below the critical value throughout the simulation, except at B1 in Scenario 1. In Scenario 1, visibility drops to the critical value of 10 m at 314 s in A1 and below the critical value at 313 s and 335 s in B1 in Scenarios 2 and 3, respectively.

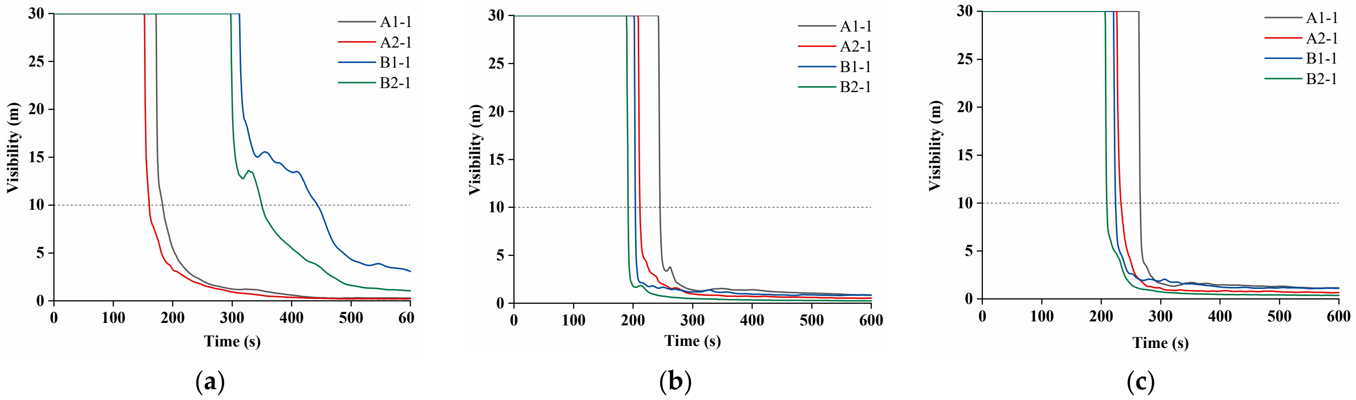


Figure 8. Visibility curves at corridors with time for different scenarios. (**a**) Scenarios 1. (**b**) Scenarios 2. (**c**) Scenarios 3.

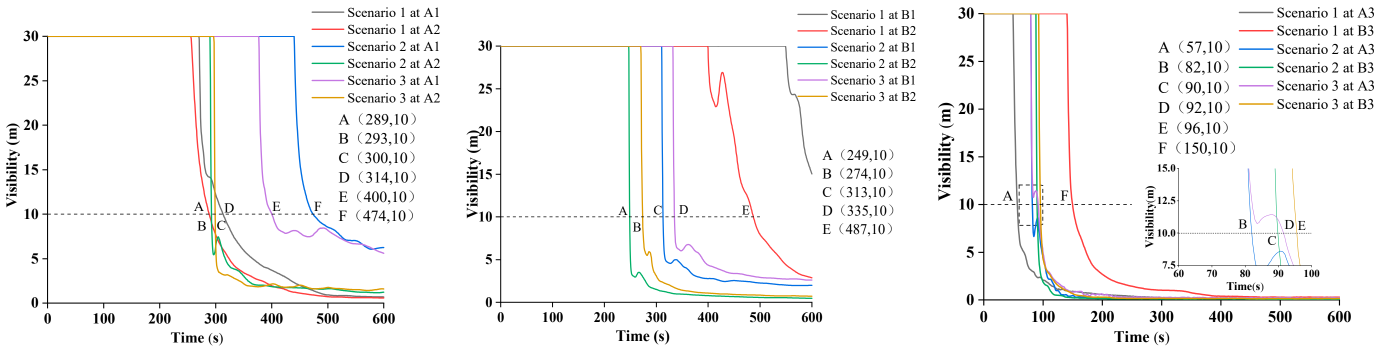


Figure 9. Time-visibility variation curves at safety exits for different scenarios.

3. Personnel Evacuation Simulation Analysis

3.1. Personnel Evacuation Model Construction

The lightened BIM model was imported into Pathfinder software for each of the above fire scenarios. Based on the characteristics of the construction site and the human body signs, the model is modified and refined in the software to obtain the Pathfinder evacuation model.

Pathfinder can simulate the behavior of escapees in specific places and environments [13]. Site construction personnel can be divided into four categories: young men, young women, middle-aged men, and middle-aged women. According to Chinese national statistics, the average age of Chinese migrant workers in 2021 is 41.5 years, so the paper sets the staffing ratio as shown in Table 5. The speed of evacuation varies considerably between different types of people. Emergency evacuation parameters, including physical and behavioral parameters, are set in Pathfinder software according to the characteristics of the people. Based on the actual personnel input on the construction site, a mock-up of 250 personnel on the construction site was drawn up, with the proportion of different types of personnel shown in Table 5. The initial state of personnel is random distribution, i.e., 250 construction personnel are randomly distributed in different working areas on the 3rd and 4th floors, and the distribution of personnel can be seen in Figure 10, with 175 construction site personnel proportionally distributed in the main working area on level 3 and 75 on level 4.

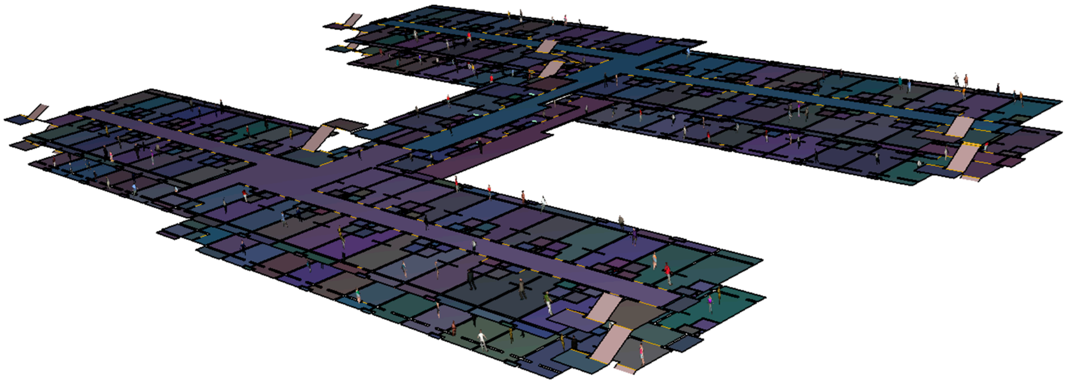


Figure 10. Analysis model for egress simulation.

If a fire occurs, the corridor reaches a dangerous state quickly, and it is unsafe for people to pass through. People in areas A and B cannot cross evacuate through the corridors, so consider evacuating people in separate areas and consider the available safe evacuation time for areas A and B, respectively. When conducting evacuation simulations, people can choose a safe exit in the area for evacuation.

Table 5. Physical signs and behavioral data for different types of people.

Personnel Category	Young Men	Young Women	Middle-Aged Men	Middle-Aged Women
Shoulder width (mm)	41	38	41.9	39.5
Height (mm)	169.7	158.0	167.1	155.8
Plane speed (m/s)	1.95	1.79	1.84	1.68
Stair surface speed (m/s)	1.25	1.09	1.19	1.03
Proportion (%)	29.5	18.5	40.7	11.3

3.2. Analysis of Evacuation Safety

If there is a fire on a construction site, evacuating people to a safe area depends on the required safe evacuation time (RSET) and the available safe evacuation time (ASET). When RSET < ASET, personnel can be safely evacuated; conversely, construction site personnel cannot be safely evacuated [6]. The required safe evacuation time is expressed in Equation (7) [48,49].

$$\mathrm{RSET} = \mathrm{T_A} + \mathrm{T_R} + 1.5 \times \mathrm{T_M} \tag{7}$$

where: $\mathrm{T_M}$ is the evacuation time, $\mathrm{T_A}$ is the fire alarm time. Because the simulation phases selected for this paper are the main construction phase and the decoration phase, there are fewer obstacles around the building, which are more open and have higher visibility, so it is assumed that the construction workers can perceive the occurrence of the fire more quickly. $\mathrm{T_A}$ set to 60 s. $\mathrm{T_R}$ for personnel response time, considering the large size of this building and the wide distribution of people, the response time may not be particularly long, so the response time is set to 120 s [50].

Calculate the needed safe evacuation time RSET = 318.5 s. Table 6 shows the evacuation safety determination table. The analysis revealed the security of Area A in Scenario 1 and Area B in Scenario 2 was judged to be unsafe, and people could not be safely evacuated.

Analyzing the trajectory of people's behavior in the evacuation simulation to obtain the cumulative number of people evacuated from each evacuation exit, as shown in Figure 11, before optimization, it can be found the number of people evacuated from safety exits A3 and B3 is much greater than the other exits. However, fire affects safety exits A3 and B3 the most, while other exits are relatively safe but less utilized. This paper considers optimizing safety exit personnel passage rates and diversifying personnel. This means that people are zoned according to the location of the evacuation exits, with people in different areas using different evacuation exits. People evacuate by choosing the exit closest to them. All with the same physiological parameters as before the optimization.

Table 6. Safety determination table.

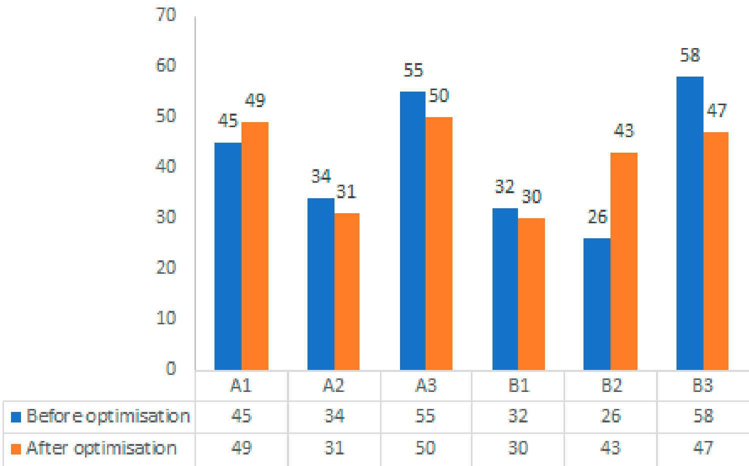
Scenarios	Region	ASET/s	RSET/s	Security
One	A	314	318.5	Unsafe
	B	-	318.5	Safe
Two	A	474	318.5	Safe
	B	313	318.5	Unsafe
Three	A	400	318.5	Safe
	B	335	318.5	Safe

As can be seen from the optimized data analysis in Figure 11, the total number of evacuees at exits A3 and B3 decreased from 55 and 58 to 50 and 47, respectively, after the diversion of personnel. In contrast, the total number of evacuees at exits A1 and B2 increased significantly, respectively, from 45 and 26 before the evacuation to 49 and 43.

And when analyzing people's behavior during the evacuation process, it was found the excessive number of people on the construction site could affect the overall evacuation speed. The number of people on the construction site is, therefore, optimized based on optimizing the passage rate of people at safety exits and reducing the density of people within the construction plane. The overall headcount was optimized to 200, with a proportional reduction of 35 staff on the third and 15 on the fourth floors. Figure 12 compares the latest time each safety exit is used for 250 and 200 people. The analysis shows a reduction in the latest use time of each security exit, with the greatest reduction in time at exit B2, from 66.3 to 58. Among the exits, the longest time used is exit B1, with a total evacuation time of 58 s for 200 people. The shortest is Exit B2, which at 200 people, has no one passing through after 49 s.

The total evacuation time after optimization is 58 s. The calculation shows that RSET= 267 s, less than 314 s for Scenario 1, and 313 s for Scenario 2; satisfying RSET < ASET, the construction site is considered safe, and all personnel can be safely evacuated.

Through the numerical simulation study of the "I" type building, it can be found that A1, A2, B1, and B2 are the better evacuation exits, and the evacuees can be guided to evacuate safely through the better evacuation exits by increasing the directional signs and guiding by the management personnel. When operations are carried out on the construction site, the site manager shall control the number of personnel on the site, which shall not exceed 250. After controlling the number of personnel and optimizing the safety exit personnel passage rate, the personnel in this simulation scenario can complete the safe evacuation. Through the simulation results, it is recommended that the construction unit should do a good job in the management of electricity, gas, fire, and flammable and explosive substances, prohibit non-professionals from carrying out fire operations; rational planning of the layout of the construction site should ensure that the fire evacuation channel is unobstructed. At the same time, evacuation drills should be carried out regularly to ensure that construction workers have the basic self-help escape ability.



	A1	A2	A3	B1	B2	B3
Before optimisation	45	34	55	32	26	58
After optimisation	49	31	50	30	43	47

Figure 11. Total number of people evacuated from different safety exits before and after optimization.

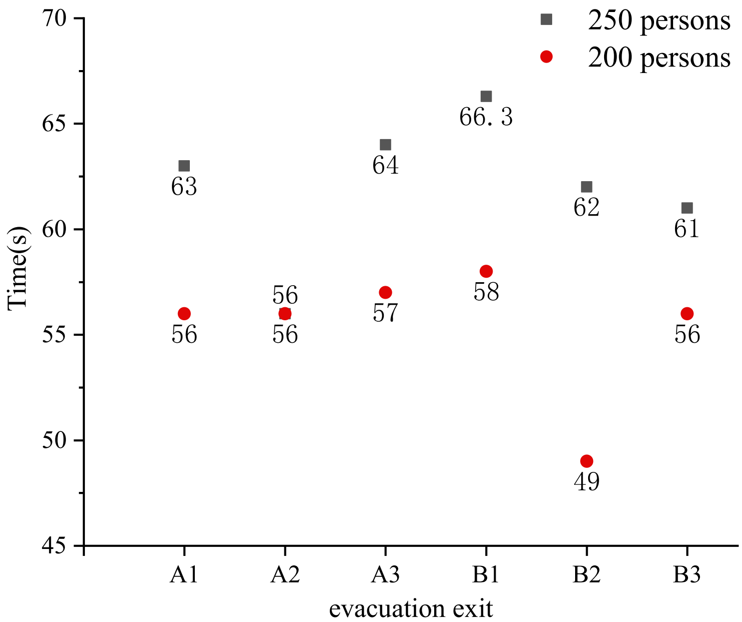


Figure 12. Latest time of use of each safety exit for 250 and 200 persons.

4. Conclusions

Managing fire safety on construction sites is a crucial part of the current construction site safety research. In this study, fire and personnel evacuation simulations were carried out on the construction site, and the following conclusions were drawn:

1. The peak temperature in Scenario 1 and the dispersion area for high CO concentrations are greater than in Scenario 3. Burning decorative materials in open spaces is a greater hazard than in small spaces, so avoid large accumulations of flammable materials in open spaces;
2. During the simulation, the visibility and temperature-affected areas in Scenario 3 and Scenario 2 are roughly the same. Still, the CO output in Scenario 3 is much higher than that in Scenario 2, and too high a CO concentration will cause harm to the human body. Compared with the main construction stage, the decoration stage is more dangerous, so the management of the decoration stage should be strengthened;
3. Through the coupling simulation test of fire and personnel evacuation, personnel behavior in the evacuation is analyzed, and the safety of Scenario 1 and Scenario 2 evacuation is insufficient. Optimize safety exit passage rates and reduce personnel on the construction site to 200. After optimization, the required safety evacuation time is

267 s, smaller than 314 s in Scenario 1, and 313 s in Scenario 2, and all Scenarios meet the safe evacuation standard;

4. Analysis of the evacuation paths of people before optimization shows that exits A3 and B3 are highly utilized, while exits A1, B1, A2, and B2 are less utilized. It is recommended to improve evacuation guidance factors and increase diversion management, for example, by adding clear signage and increasing the management of guides. There is a low evacuation speed for construction sites with complex traffic planes; Therefore, the construction company must not increase the number of laborers indefinitely to speed up the construction period. Construction workers may be unable to complete a safe evacuation within the required time if a hazard occurs. And in the construction site management, it is necessary to reasonably plan the stacking position of materials, equipment, and other items, reduce the load of the construction plane, and ensure the smooth evacuation stairs;
5. In this paper, when studying the change law of the fire environment factors in the construction site, the "I" type buildings which are frequently used in China are selected. As China's construction industry continues to grow, there will be many construction sites of different structural types. Therefore, the evacuation of people from different structure types of construction under different fire conditions can be further investigated, and this study can also serve as a basis for further research.

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