Journal of Operational and Strategic Analytics
https://www.acadlore.com/journals/JOSA

Fire Risk Assessment and Scenario Simulation for Employee Dormitory Buildings

Qiang Li, Zaohong Zhou*, Yunbin Sun, Hongjun He

School of Information Management and Mathematics, Jiangxi University of Finance and Economics, 330013 Nanchang, China

* Correspondence: Zaohong Zhou (zhouzaohong@jxufe.edu.cn)

Received: 06-24-2024 **Revised:** 09-13-2024 **Accepted:** 09-22-2024

Citation: Q. Li, Z. H. Zhou, Y. B. Sun and H. J. He, "Fire risk assessment and scenario simulation for employee dormitory buildings," *J. Oper. Strateg Anal.*, vol. 2, no. 3, pp. 193–214, 2024. https://doi.org/10.56578/josa020305.

Abstract: Fire, as an unpredictable and highly destructive hazard, poses significant risks to densely populated environments such as employee dormitory buildings. This study aims to evaluate fire risks in such facilities and propose effective fire safety management strategies to enhance fire prevention capabilities and evacuation efficiency. An index system of fire risk influencing factors specific to employee dormitory buildings was established through an extensive review of relevant literature and field interviews. The Ordinal Priority Approach (OPA), a multi-attribute decision analysis method based on ordinal data, was employed to quantify the weights of these influencing factors using a linear programming model. Subsequently, fire scenarios were simulated using PyroSim software, focusing on the top two critical influencing factors to assess evacuation times and safety conditions. The analysis identified the condition of fire-fighting facilities, ventilation within dormitory buildings, the use of high-power electrical appliances, and smoking behaviors among employees as key determinants of fire risk. The simulation results indicated that visibility during a fire significantly affects the available safe evacuation time. While natural ventilation was found to moderately mitigate fire spread, its impact was less pronounced compared to the effectiveness of automatic sprinkler systems. The reliability of the simulation outcomes was further validated through expert interviews, ensuring the practical applicability of the findings. Based on the outcomes of risk analysis and scenario simulations, several fire safety improvement measures were proposed. These include upgrading fire-fighting facility standards, optimizing natural ventilation systems, and implementing comprehensive fire safety education and training programs. The insights derived from this research provide a robust scientific foundation and actionable recommendations for the fire risk management of employee dormitory buildings.

Keywords: Employee dormitory buildings; Fire risk analysis; Ordinal Prioritization Approach (OPA); PyroSim simulation

1 Introduction

Fire is a catastrophic event with immense destructive power, whose combustion process is difficult to control effectively in space or time, posing a serious threat to people's safety [1]. For instance, during the development of a fire, the harmful gases, high temperatures, and dense smoke produced by the fire all pose a serious threat to human health, increasing the difficulty and danger of escape. This risk is particularly prominent in densely populated employee dormitory buildings. These dormitories typically house a large number of staff. In the event of a fire, due to the limitations of the building structure and the insufficiency of evacuation facilities, such as internal corridor designs and a limited number of evacuation stairs, it can easily lead to difficulties in personnel evacuation and increase the risk of casualties. Moreover, many old dormitory buildings lack modern fire-fighting facilities, such as smoke detectors, automatic sprinkler systems, and mechanical smoke exhaust systems, which further shorten the available safe evacuation time for evacuating personnel. In March 2018, a fire caused by smoking in a southern factory's employee dormitory resulted in 21 deaths and seven serious injuries when an employee accidentally dropped a cigarette butt on the bed, igniting the bedsheet and rapidly spreading the fire. On the early morning of April 22, 2021, a fire occurred in an employee dormitory near the Civic Center in Jiashan County, Zhejiang Province, which was understood to be caused by a short circuit in a computer charger, resulting in one death and two injuries. In the early morning of December 23, 2021, a fire accident occurred in an employee dormitory in Hengye Mingduyuan, Tongguan District, Lianyungang City, Jiangsu Province, causing ten deaths and six injuries. From the above cases, it can be seen that once a fire accident occurs in an employee dormitory, whether it is a minor or a severe fire, it can lead to serious consequences. To effectively guard against the fire hazards in employee dormitories, targeted prevention is necessary. It is essential to analyze the fire risks of such places and simulate the occurrence and development process through simulation to respond scientifically.

Scholars have been continuously conducting research on dormitory fires, and fire risks can be identified and managed through risk assessment methods [2]. Therefore, in the field of fire risk research, various fire safety risk assessment methods have taken a dominant position [3]. These risk assessment methods can be broadly divided into three categories: qualitative methods, quantitative methods, or a combination of both. Scholars both domestically and internationally have used various risk assessment methods to delve into the fire risks of dormitories. For example, Khajehnasiri et al. [4] employed the Fire Risk Index Method (FRIM-MAB) for a quantitative assessment of fire risk in the student dormitories of Qazvin University of Medical Sciences. By utilizing FRIM-MAB version 2.1, they identified 17 key parameters affecting the fire risk index, and weighted these parameters and their sub-parameters, ultimately calculating the fire risk index for each section on a scale of 1 to 5. Zhang and Yu [5] proposed a Bayesian network analysis model to assess fire safety in university dormitories from both quantitative and qualitative perspectives. This model integrated expert knowledge and a wealth of literature data, established a relevant indicator system and Bayesian model, and validated its accuracy using data from the past decade, thereby extracting key factors of fire hazards through reverse reasoning analysis of nodes. Hassanain et al. [3] criticized fire risk assessment methods that rely on current regulations and standards and proposed a new Fire Safety Rating System (SH-FSRS). They used literature review and expert consultation and applied the Analytic Hierarchy Process (AHP) to determine the key attributes and weights of fire safety to achieve a more comprehensive assessment. However, relying solely on these risk assessment methods to analyze the fire risks in dormitories makes it difficult to consider the dynamic safety issues within the dormitories during a fire.

With the rapid development of technology, the National Institute of Standards and Technology (NIST) released the Fire Dynamics Simulator (FDS) software in February 2000 [6]. The emergence of computer numerical simulation technology has successfully addressed this issue, and this technology has become the main method for scholars at home and abroad to study various fire processes and evacuations. For example, Tabaczenski et al. [7] used computer simulation technology to reproduce a fire in a burned residential bedroom in Recife, Pernambuco, Brazil, employing the FDS to simulate gas temperature changes and comparing them with experimental data. The results showed that the temperatures obtained through FDS were consistent with those observed in the experiments. Hostetter and Naser [8] conducted 327 simulations of the evacuation process of 1-3 wheelchair users in low-rise apartment (dormitory) buildings through simulation experiments, examining evacuation times and determining the impact of structural assistive tools and obstacles. Wang et al. [9] used PyroSim and Pathfinder software (2019 edition) to simulate the spread of fire in multi-story college student dormitory buildings, aiming to assess the impact of fire on public safety and optimize evacuation strategies. In order to solve the emergency evacuation problem in highly densely populated university dormitories in China, Huang et al. [10] constructed Building Information Modeling (BIM) of the student dormitory buildings at the Xuhui campus of Shanghai Normal University, and, based on this, used the Unity platform for agent-based modeling (ABM) simulation of the evacuation process. Taking a student dormitory as the research subject, Jeon et al. [11] emphasized the importance of planning multiple paths and considering the differences in Available Safe Egress Time (ASET) in different areas during fire evacuation by calculating the ASET and Required Safe Egress Time (RSET) of the student dormitory. However, most of the aforementioned studies focus on the fire risk analysis of student dormitories, with insufficient attention to the fire safety issues in employee dormitories. The fire hazards in employee dormitories may be more severe because, although it is generally believed that adults have a stronger fire prevention awareness than students, adults may be more likely to engage in behaviors that increase fire risks, such as smoking or improper use of electrical appliances. In addition, although there have been studies analyzing the fire risk of dormitory buildings through various risk assessment methods and many scholars have used simulation software for fire scenario simulations, there is still room for improvement in combining the two areas of research.

Therefore, this study takes a certain employee dormitory building as the research subject. First, a fire risk influencing factor index system for the employee dormitory building was constructed through literature research and interview methods. Secondly, the OPA was applied to determine the weights of each influencing factor index. Then, different fire scenarios were set using the fire dynamics simulation software PyroSim, targeting the top-ranked influencing factor indices, and scenario simulations were conducted. The available safe evacuation time for personnel under different fire scenarios was compared to verify the accuracy of the fire risk analysis results and to explore the dynamic safety issues in fire scenario simulations. Finally, based on the results of the risk analysis and fire simulation, combined with the actual situation of the employee dormitory building, reasonable rectification measures were proposed. The aim is to provide a scientific basis for the fire safety management of employee dormitory buildings and to offer some reference for fire risk assessment of similar structures.

2 Methodology

This study proposes a fire risk analysis method that combines the OPA with fire scenario simulation technology, which is divided into two main parts. The first part involves the determination of indicator weights based on the OPA. Initially, experts in relevant fields were invited and ranked according to corresponding scoring criteria. Then the experts prioritized the attributes related to fire risk influencing factor indicators based on their professional knowledge. Subsequently, each expert ranked the fire risk influencing factor indicators according to each attribute. Finally, a linear programming model was constructed from the data formed in the previous steps and solved to calculate the weights of each fire risk influencing factor indicator. The second part is the fire scenario simulation based on the PyroSim software, which serves two purposes. First, analyzing fire risk using only the OPA makes it difficult to consider the dynamic safety issues during the fire occurrence process; conducting fire scenario simulation with PyroSim software can effectively address this issue. Secondly, considering the credibility of the OPA's results on fire risk, different fire scenarios were set up in this study for the fire risk influencing factor indicators with higher weights to verify the accuracy of the fire risk analysis results through scenario simulation.

2.1 OPA Method

The OPA is a multi-attribute decision-making method that can be used for individual or group decision-making. In group decision-making, this method first determines the experts and their priorities. The priority of experts can be determined based on their experience or knowledge. After ranking the experts, each expert prioritizes the attributes. At the same time, each expert ranks the alternative solutions based on each attribute and sub-attribute. Finally, by solving the linear programming model established by this method, the weights of attributes, alternative solutions, experts, and sub-attributes are obtained simultaneously [12]. Compared to most multi-criteria decision analysis methods, such as AHP, Analytic Network Process (ANP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Principal Component Analysis (PCA), etc., this method has two significant advantages. First, this method does not require the use of pairwise comparison matrices, decision matrices (no numerical input is needed), normalization methods, averaging methods to aggregate expert opinions (in group decision-making), and linguistic variables; secondly, in this method, experts can only comment on the attributes and alternative solutions for which they have sufficient knowledge and experience, and they can abstain from commenting on attributes for which they lack sufficient knowledge, thereby improving the accuracy and decision-making efficiency of the final results [13]. So far, the OPA has been widely used in various fields. For example, Mahmoudi and Javed [14] proposed a "hybrid game theory and ordinal priority method" as a new solution for the development of cross-border non-renewable resources, aiming to supervise and promote sustainable competition among countries through the intervention of international organizations. Pamucar et al. [15] proposed a new extension of the ordinal priority ranking method (OPA-P algorithm) based on image fuzzy set theory, aiming to provide a set of effective decision support tools for sustainable transportation planning.

Table 1. Quantitative evaluation criteria for expert level

Professional Title		**Years of Professional Experience**		**Highest Educational Degree**		**Number of Papers Published in the Field of Building Fire**	
Qualitative Ranking	**Quantitative Scoring**	**Qualitative Ranking**	**Quantitative Scoring**	**Qualitative Ranking**	**Quantitative Scoring**	**Qualitative Ranking**	**Quantitative Scoring**
Junior	1	Less than 2 years	1	High school	1	Fewer than 5 papers	1
Intermediate	2	2 to 5 years	2	Associate degree	2	5 to 10 years	2
Associate senior	3	5 to 10 years	3	Bachelor's degree	3	10 to 15 papers	3
Full senior	4	10 to 20 years	4	Master's degree	4	More than 15 papers	4
		More than 20 years	5	Doctoral degree	5		

The specific calculation steps of the OPA are as follows:

Step 1: Identification and ranking of experts. The title is usually positively correlated with individual practical standards, reflecting the expert's experience and skill level in a specific field; the length of service is often proportional to an individual's practical experience and professionalism; educational qualifications represent the expert's theoretical knowledge level and are closely related to theoretical standards; the number of papers published in the field of building fires can reflect the depth of the expert's research and academic influence in that area. Therefore, scores were equally assigned to four evaluation criteria in this study, namely, title, length of service, educational qualifications, and the number of papers published in the field of building fires. This scoring method can balance the strengths and weaknesses of different experts, ensuring that the professional expertise and contributions of each expert are fairly evaluated. The specific evaluation criteria are shown in Table 1.

Step 2: Attribute determination and prioritization based on the professional knowledge of experts. As for some experts, if certain attributes are not critical, or they lack sufficient knowledge to comment on the inclusion of specific attributes, they are free not to include these attributes in the ranking process and the mathematical model.

Step 3: Determination and ranking of the alternative solutions based on each attribute by experts.

Step 4: Construction of the following linear programming model based on the data from the previous steps, and solving of the model using software such as LINGO or Matlab to find the weights of the attributes and rank the alternative solutions.

$$\mathrm{Max}\, Z s.t Z \leq r_i \left(r_j \left(r_k \left(W_{ijk}^{r_k} - W_{ijk}^{r_k+1} \right) \right) \right) \forall i, j \text{ and } r_k \tag{1}$$

$$Z \leq r_i r_j r_m W_{ijk}^{r_m} \forall i, j \text{ and } r_m \tag{2}$$

$$\sum_{i=1}^{p} \sum_{j=1}^{n} \sum_{k=1}^{m} W_{ijk}^{r_m} = 1, W_{ijk} \geq 0 \quad \forall i, j \text{ and } k \tag{3}$$

where, Z represents the objective function; $r_i(i = 1, \ldots, p)$ represents the rank of expert $i; r_j(j = 1, \ldots, \mathrm{n})$ represents the rank of attribute $j; r_k(k = 1, \ldots, \mathrm{m})$ represents the rank of alternative solution k; and w_{ijk} represents the weight of alternative solution k under attribute j for expert i. In this context, Z is not subject to any sign restrictions.

The weight w_k for each alternative solution can be calculated by the following formula:

$$w_k = \sum_{i=1}^{p} \sum_{j=1}^{n} W_{ijk} \forall k \tag{4}$$

The weight w_j for each attribute can be calculated by the following formula:

$$w_j = \sum_{i=1}^{p} \sum_{k=1}^{m} W_{ijk} \quad \forall j \tag{5}$$

The weight w_i for each expert is calculated by the following formula:

$$w_i = \sum_{j=1}^{n} \sum_{k=1}^{m} W_{ijk} \quad \forall i \tag{6}$$

2.2 PyroSim Software Introduction

PyroSim software, developed by Thunderhead Engineering, is a powerful fire dynamics simulation tool based on FDS technology. It can simulate and predict the movement, temperature, and concentration of smoke and toxic gases such as carbon monoxide (CO) during a fire, providing users with an intuitive visual interface that allows them to build and view simulation models without writing code. Compared to traditional FDS, PyroSim's advantage lies in its ability to allow users to preview models in real-time during the construction process, which not only improves the accuracy of model building but also makes the simulation process more intuitive and efficient [16]. PyroSim's comprehensive functionality covers various aspects, including fire scenario setup, grid division, fire source configuration, and combustion behavior settings. It can also display the calculation results of FDS and use Smokeview software for animated display, further enhancing the visualization and analysis capabilities of simulation results. These advantages make PyroSim a powerful tool in the field of fire dynamics simulation, effectively predicting the flow of fire smoke, fire temperature, and the distribution of toxic and harmful gas concentrations, providing strong technical support for fire safety assessment and emergency response.

During the operation of PyroSim, users first need to create a fire simulation model within PyroSim, which includes defining the geometric shape and spatial layout of the building, as well as setting the basic parameters required for the simulation, or preparing a detailed BIM model that includes information on building geometry, material properties, spatial layout, etc., and then converting the model to the corresponding format before importing it into PyroSim. Then material properties and heat sources need to be added to the model, which involves specifying the thermophysical properties of different building materials and simulating the location and intensity of the fire. The boundary conditions need to be set, including vents and other factors that may affect fire behavior. After completing these settings, the simulation can be initiated, and PyroSim can calculate the distribution of temperature, smoke, and toxic gases during the development of the fire. Finally, the simulation results can be analyzed, which typically involves viewing animations generated by Smokeview and data charts provided by PyroSim to assess the effectiveness and impact of the fire simulation.

3 Case Study

This study focuses on a specific employee dormitory building, which is a three-story office and residential building, with the first floor designated as the office area and the second and third floors as the residential areas. The dormitory building has only one staircase, and due to its early construction, most of the building facilities are quite outdated. Moreover, the dormitory lacks fire protection facilities, such as sprinkler systems, emergency lighting systems, and fire detection and alarm equipment. Therefore, conducting a fire risk analysis for such premises can effectively identify and assess potential fire risks, which is crucial for ensuring the life and property safety of the employees.

3.1 Construction of the Fire Risk Impact Factor Indicator System for Employee Dormitory Buildings

This study initially identified the fire risk factors affecting employee dormitory buildings using literature research. Subsequently, interviews were conducted with residents within the employee dormitory building, totaling 17 residents. Through the analysis of these interview results, the preliminary fire risk factors were further supplemented and revised. Ultimately, 15 influencing factors were determined, which were summarized from five dimensions: personnel, building, environmental, equipment, and management factors. The fire risk impact factor indicator system for employee dormitory buildings is detailed in Table 2.

3.2 Determination of Indicator Weights Based on the OPA Method

(a) Identification and ranking of experts

This study invited three experts from universities and research institutes who are engaged in the field of building fire research. Among these three experts, one had been a senior practitioner in the direction of building fire safety before joining the university, thus possessing strong practical knowledge but potentially lacking in theoretical knowledge. The other two experts, although having a shorter duration in the field of building fire safety, have conducted research in this area for many years, possessing a comprehensive theoretical knowledge framework and achieving certain results. The specific evaluation criteria are shown in Table 1. Based on the sequence of expert interviews, the three experts were numbered as E1 to E3. The final scoring results are shown in Table 3.

From Table 3, it can be seen that based on the total scores of the three experts, the ranking result is E2 > E1 > E3.

(b) Ranking and weight calculation of the five dimensions

Based on the ranking data from the experts and their sorting of the five dimensions according to the degree of fire risk impact, the weights of the five dimensions were calculated using the OPA. In the calculation process, the experts were ranked in three positions, corresponding to the three experts; the attribute was ranked in one position, corresponding to the attribute "degree of fire risk impact"; and the alternatives are ranked in five positions, corresponding to the experts' ranking of the five dimensions based on the degree of fire risk impact. The ranking results are shown in Tables 4 and 5.

In the table above, E1, E2, and E3 represent the expert IDs; C1 represents the attribute of the degree of fire risk impact; and A1, A2, A3, A4, and A5 represent the five dimensions of personnel, building, environmental, equipment, and management factors, respectively.

(c) Ranking and weight calculation of influencing factors under each dimension

Based on the ranking data from experts, the calculated weights of the five dimensions, and the ranking data of influencing factors under each dimension according to their likelihood of occurrence and degree of harm assessed by experts, the weights of influencing factors under each dimension were calculated using the OPA. In the calculation process, the experts were ranked in three positions, corresponding to the three experts; the attributes were ranked in two positions, corresponding to the attributes "likelihood of occurrence" and "degree of harm"; and the alternatives were ranked in five positions, corresponding to the experts' ranking of influencing factors under each dimension.

Considering the hierarchical relationship between the five dimensions and the influencing factors under each dimension, the influencing factor indicators obtained were corrected so that the sum of the weights of the influencing factors under each dimension equals 1, ultimately obtaining the weight of the fire risk influencing factor indicator system for employee dormitory buildings. Taking the dimension of building factors as an example, the ranking results are shown in Tables 6 and 7. The final calculation results are shown in Table 8.

Table 2. Index system of fire risk influencing factors in employee dormitory buildings

Dimension	Code	Influencing Factor	Explanation	References
Personnel factor	S_1	Employee smoking behavior	Employee smoking causes fire.	Zhang et al. [17]
	S_2	Employee misuse of high-power electrical equipment	Employee misuse of high-power electrical appliances causes fire.	Zhang et al. [17], Wang et al. [18]
	S_3	Employee unauthorized tampering with temporary wiring	Employee unauthorized tampering with temporary wiring causes fire.	Zhang et al. [17], Wang et al. [18]
Building factor	S_4	Building fire resistance rating	The building's fire resistance rating is too low.	Zhang et al. [17], Liu et al. [19], Marantika et al. [20]
	S_5	Types of building decoration materials	Building materials are flammable and may contain toxic substances.	Liu et al. [19], Joo et al. [21]
	S_6	Division of fire and smoke compartments	The division of fire and smoke compartments is unreasonable.	Zhang et al. [17], Liu et al. [19]
	S_7	Building fire load	The building's fire load is excessive.	Zhang et al. [17], Liu et al. [19]
	S_8	Number of emergency exits	The number of emergency exits is too few.	Zhang et al. [22]
Environmental factor	S_9	Weather conditions	Hot and dry weather	Liu et al. [19], Joo et al. [21]
	S_{10}	Ventilation conditions in the dormitory building	Whether the dormitory windows are open during a fire.	Liu et al. [19], Joo et al. [21]
Equipment factor	S_{11}	Quality of electrical equipment (aging)	Premature aging of electrical equipment causes fire.	Zhang et al. [17], Wang et al. [18]
	S_{12}	Condition of firefighting facilities	Whether the building has sprinkler systems, emergency lighting systems, fire detection and alarm equipment, and other firefighting facilities, or whether these facilities have become inoperative.	Zhang et al. [17], Wang et al. [18], Liu et al. [19], Marantika et al. [20], Joo et al. [21]
Management factor	S_{13}	Conducting fire safety training and drills	Whether enterprises conduct fire drills at regular intervals.	Zhang et al. [17], Liu et al. [19]
	S_{14}	Implementation of preventive rectification measures	Whether rectification of areas with problems identified in early fire inspections is implemented.	Zhang et al. [17], Liu et al. [19], Marantika et al. [20]
	S_{15}	Fire emergency response plan	The operability of emergency plans	Zhang et al. [17], Liu et al. [19]

Table 3. Quantitative scoring results of expert levels

Expert ID	Title Score	Years of Experience Score	Highest Education Score	Publications in Building Fire Field Score	Total Score
E1	3	1	5	2	11
E2	4	4	4	1	13
E3	2	1	5	1	9

Table 4. Expert ranking and ranking results of the degree of impact of fire risk attributes by experts

Expert	Ranking	Attribute	Ranking
E1	2	E1C1	1
E2	1	E2C1	1
E3	3	E3C1	1

Table 5. The ranking results of alternative solutions by experts based on each attribute

	E1 C1	E2 C1	E3 C1
A1	1	2	3
A2	4	4	5
A3	2	3	1
A4	3	1	2
A5	5	5	4

Table 6. Expert ranking and the ranking results of experts on the likelihood of occurrence and degree of harm attributes

Expert	Ranking	Attribute	Ranking
E1	2	E1C1	1
		E1C2	2
E2	1	E2C1	2
		E2C2	1
E3	3	E3C1	2
		E3C2	1

Table 7. The ranking results of alternative solutions by experts based on each attribute in the dimension of architectural factors

	E1		E2		E3	
	C1	C2	C1	C2	C1	C2
A1	1	3	4	2	4	2
A2	2	2	3	4	3	4
A3	3	5	1	5	2	5
A4	4	4	2	1	5	1
A5	5	1	5	3	1	3

In the table above, E1, E2, and E3 represent the expert IDs; C1 and C2 represent the attributes of ”likelihood of occurrence” and ”degree of harm,” respectively; and A1, A2, A3, A4, and A5 represent the influencing factors S_4 to S_8 under the dimension of building factors in sequence.

From Table 8, it can be seen that in the comprehensive weights calculated using the OPA, the condition of firefighting facilities (S_{12}), the ventilation conditions in the dormitory building (S_{10}), the behavior of employees misusing high-power electrical equipment (S_2), and employee smoking behavior (S_1) have the highest comprehensive weights. Therefore, collectively, these four influencing factors can be considered the most critical factors affecting the fire risk in employee dormitory buildings, and their ranking in terms of the comprehensive weight is $S_{12} > S_{10} > S_2 > S_1$.

Since relying solely on this fire risk analysis method to assess the fire safety of employee dormitory buildings fails to consider the dynamic safety issues during the development of a fire, and considering the credibility of the fire risk analysis results, this study takes the employee dormitory building as the research subject. Through the fire dynamics simulation software PyroSim, different fire scenarios were set for the top two ranked influencing factors (S_{12} and S_{10}) based on the comprehensive weight, and scenario simulations were conducted. The simulation results under different fire scenarios and the available safe evacuation time for personnel were compared, further verifying the accuracy and reliability of the fire risk analysis results for the employee dormitory building.

Table 8. Calculation results of weight of fire risk influencing factors indicators for employee dormitory buildings

Dimension	Weight	Influencing Factor Indicator under the Dimension	Weight within the Dimension	Weight of the Influencing Factor Indicator	Ranking
Personnel factor	0.29	S_1	0.42	0.123	4
		S_2	0.47	0.138	3
		S_3	0.11	0.033	7
Building factor	0.08	S_4	0.24	0.020	10
		S_5	0.15	0.012	13
		S_6	0.15	0.012	14
		S_7	0.30	0.024	8
		S_8	0.16	0.013	12
Environmental factor	0.24	S_9	0.37	0.089	6
		S_{10}	0.63	0.150	2
Equipment factor	0.34	S_{11}	0.31	0.105	5
		S_{12}	0.69	0.233	1
Management factor	0.05	S_{13}	0.43	0.021	9
		S_{14}	0.39	0.019	11
		S_{15}	0.18	0.009	15

3.3 Establishment of the Fire Numerical Model

3.3.1 Overview of the employee dormitory building

The employee dormitory building is a three-story office and residential building, with the first floor designated as the office area and the second and third floors as the residential areas. The first floor contains eight offices, a duty room, a security room, a spare parts warehouse, and three exits, with a total construction area of 413.25 m^2; the second floor has 12 rooms, and the third floor has 15 rooms, each with an area of approximately 20 m^2 to 22 m^2, accommodating two people per room; the height of each floor is 4.2 m, and there is only one staircase in the dormitory building, with a total construction area of 1239.75 m^2. The floor plan of the first floor of the employee dormitory building is shown in Figure 1.

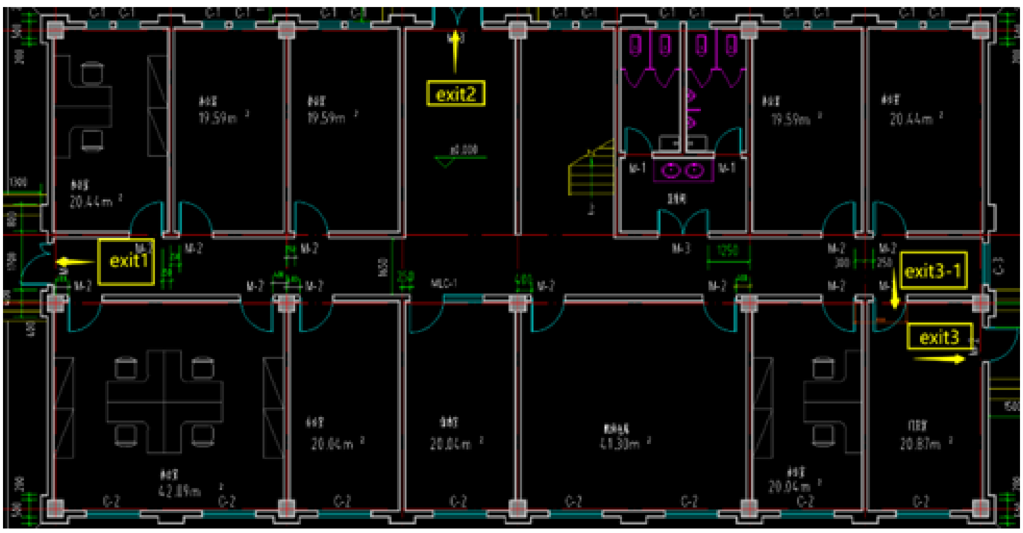

Figure 1. First floor plan of the employee dormitory building

3.3.2 Selection of the fire origin location

In fire simulation, selecting the location of the fire origin is crucial, and using the principle of the most adverse condition for location selection can simulate the worst-case scenario, which helps to save more lives in reality. When determining the location of the fire origin, several principles need to be considered comprehensively. First, flammable materials and spaces that are prone to ignition should be chosen to closely approximate real fire situations. Second, priority should be given to areas with dense populations and difficult evacuation to simulate real fire scenarios and increase the credibility of the simulation results. Based on the above, an office next to the security room on the east side of the first floor was selected as the fire source in this study, and the location of the fire source is shown in Figure 2. Firstly, people often gather in the first-floor office for meetings and work, and there is a high likelihood of fires caused by smoking or the use of high-power electrical equipment. Therefore, choosing this location as the fire source is closer to real fire situations. Secondly, if a fire occurs in the first-floor office, smoke can quickly spread to the first-floor corridor, and all the safety exits of the building are on the first floor, which means that people on the second and third floors must descend to the first-floor corridor via the central staircase and then escape through the safety exits. Therefore, this fire origin location can better simulate the worst-case scenario of fire spread in a fire scenario.

3.3.3 Setting of fire scenarios

The initial environmental temperature for the fire simulation was set at 20℃, with the simulation grid size for the employee dormitory building set at 0.3 m * 0.3 m * 0.3 m, totaling 319,770 grid cells. This simulation includes three fire scenarios, each with a simulation time of 600 seconds. In the first fire scenario, the fire source is in an office next to the security room on the east side of the first floor, with a fire source area of 0.25 m^2; the windows on both sides of the corridors on each floor are closed; the fire is caused by employees misusing high-power electrical equipment; and there is no automatic sprinkler system. Referring to the ”Technical Standard for Smoke Control Systems in Buildings” (GB 51251-2017) and combining it with actual conditions, the maximum heat release rate of the fire source was determined to be 16000 kW/m^2. To make the simulation process more realistic, the heat release rate model of the fire source was set to the t^2 model, with the fire type set to a rapid fire and a fire growth coefficient α of 0.04689 [23]. In the second scenario, the fire source location and the area remain unchanged; the windows on both sides of the corridors on each floor are open; the fire is caused by employees misusing high-power electrical equipment, with a maximum heat release rate of 16000 kW/m^2; and there is no automatic sprinkler system. In the third fire scenario, the fire source location and the area remain unchanged; the windows on both sides of the corridors on each floor are closed; the fire is caused by employees misusing high-power electrical equipment; the maximum heat release rate is 16000 kW/m^2; and an automatic sprinkler system is present. The ”Design Code for Automatic Sprinkler Systems” (GB50084-2017) was referenced for the placement of the automatic sprinkler system. Specific settings for the fire scenarios are shown in Table 9.

Table 9. Fire scene setting in employee dormitory building

Scenario	Corridor Window Status	Cause of Fire	Automatic Sprinkler System	Fire Type	Maximum Heat Release Rate of Fire Source
Scenario 1	Closed	Employees misusing high-power electrical appliances	No	Rapid fire	16000 kw/m^2
Scenario 2	Opened	Employees misusing high-power electrical appliances	No	Rapid fire	16000 kw/m^2
Scenario 3	Closed	Employees misusing high-power electrical appliances	Yes	Rapid fire	16000 kw/m^2

3.3.4 Setting of measurement points

The critical thresholds of human tolerance for temperature, visibility, CO concentration (ppm), and smoke layer height were used as criteria in this study for determining when a fire reaches a dangerous state [24–26], as shown in Table 10. Temperature sensors, visibility sensors, CO concentration sensors, and smoke layer height sensors were set up at a height of 1.8 meters from the floor at three safety exits and the entrance of the security room on the east side, as well as at the stairwell at a height of 1.8 meters from the ground on each floor [26]. The positions of the sensors on the first floor are shown in Figure 2.

Table 10. The critical danger values of each factor

Fire Products	Temperature (℃)	Visibility (m)	CO Concentration (mol/mol)	Smoke Layer Height (m)
Dangerous Critical Value	≥ 60	≤ 10	$\geq 5*10^{-4}$	≤ 2

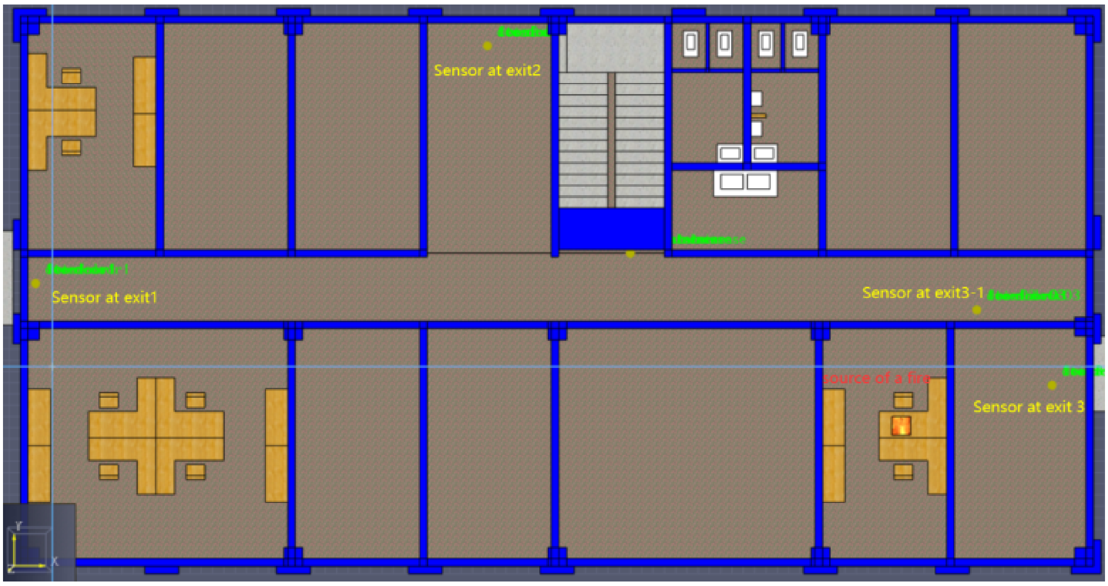

Figure 2. Fire source location and first-layer sensor setting position

3.4 Fire Simulation Results for Scenario 1

The visibility, CO concentration, temperature, and smoke layer height variation curves for Scenario 1 are shown in Figures 3 to 6.

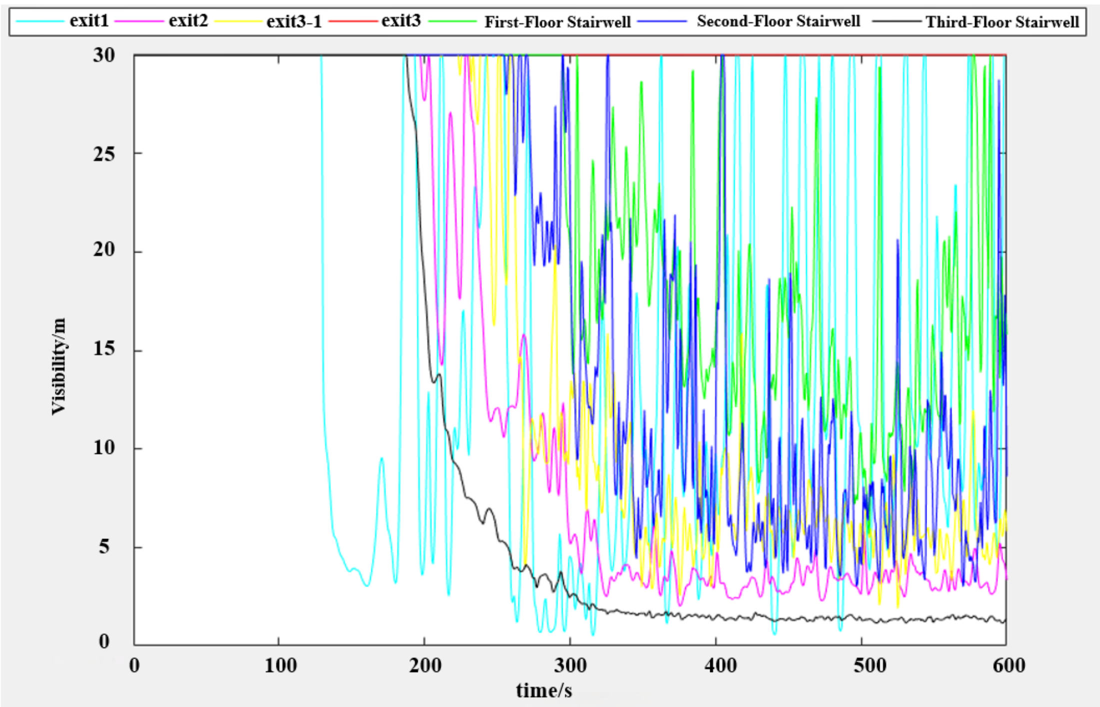

Figure 3. Visibility change curve for Scenario 1

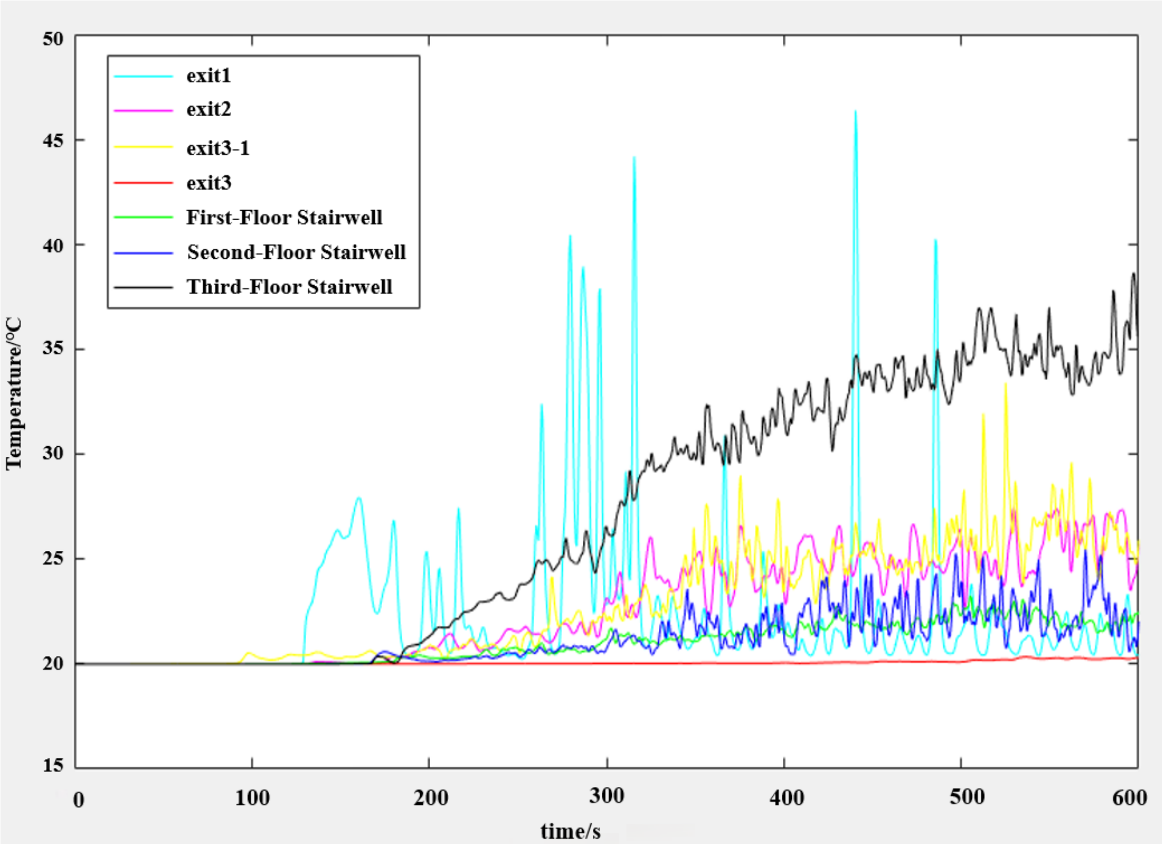

Figure 4. Temperature variation curve for Scenario 1

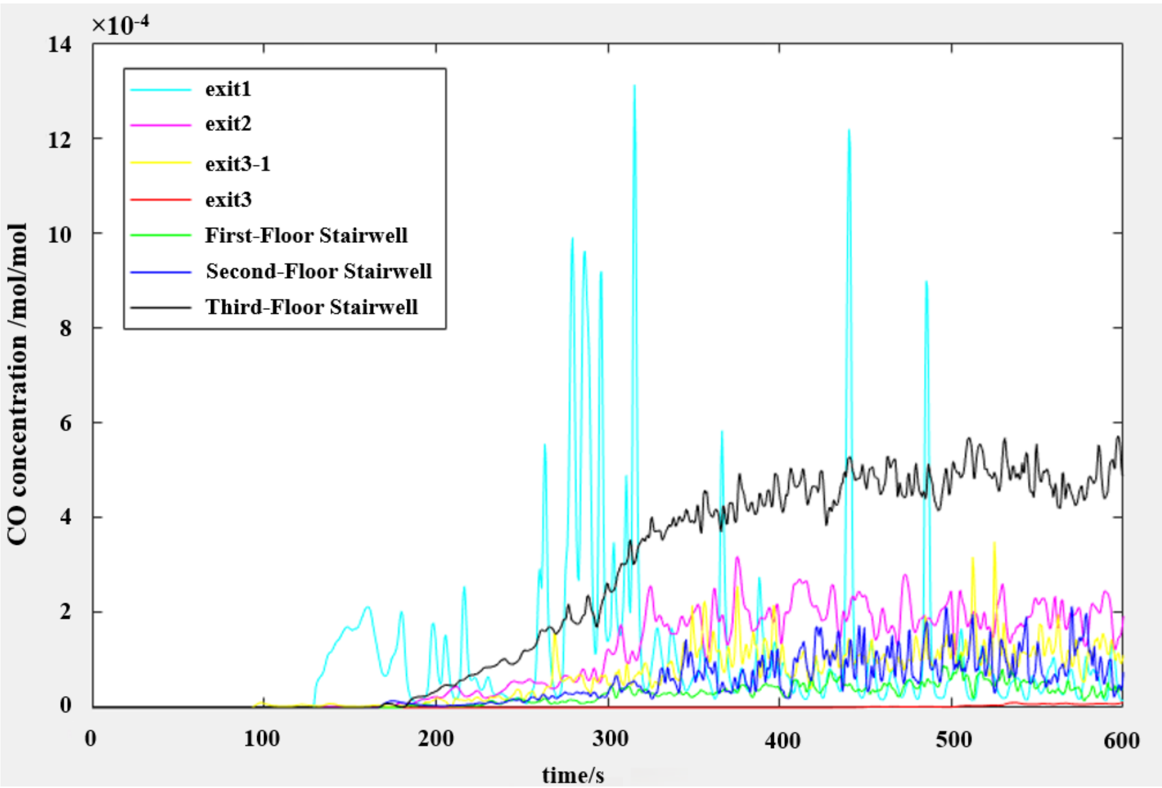

Figure 5. CO concentration variation curve for Scenario 1

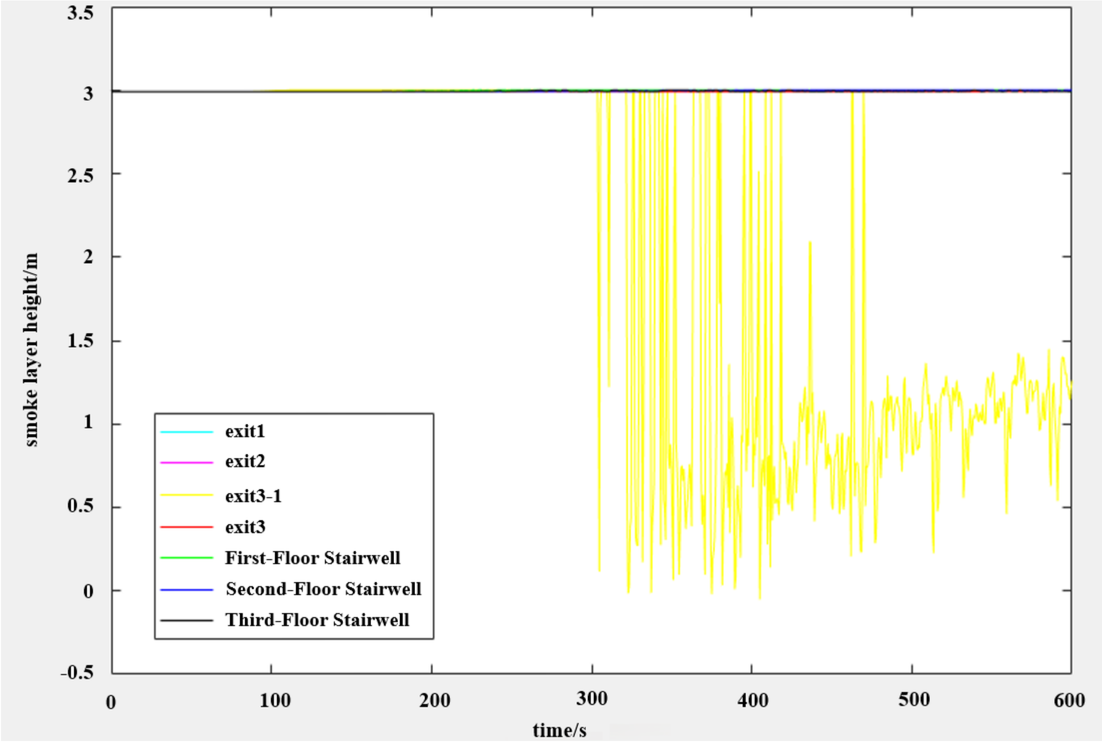

Figure 6. Smoke layer height variation curve for Scenario 1

3.5 Fire Simulation Results for Scenario 2

The visibility, CO concentration, temperature, and smoke layer height variation curves for Scenario 2 are shown in Figures 7 to 10.

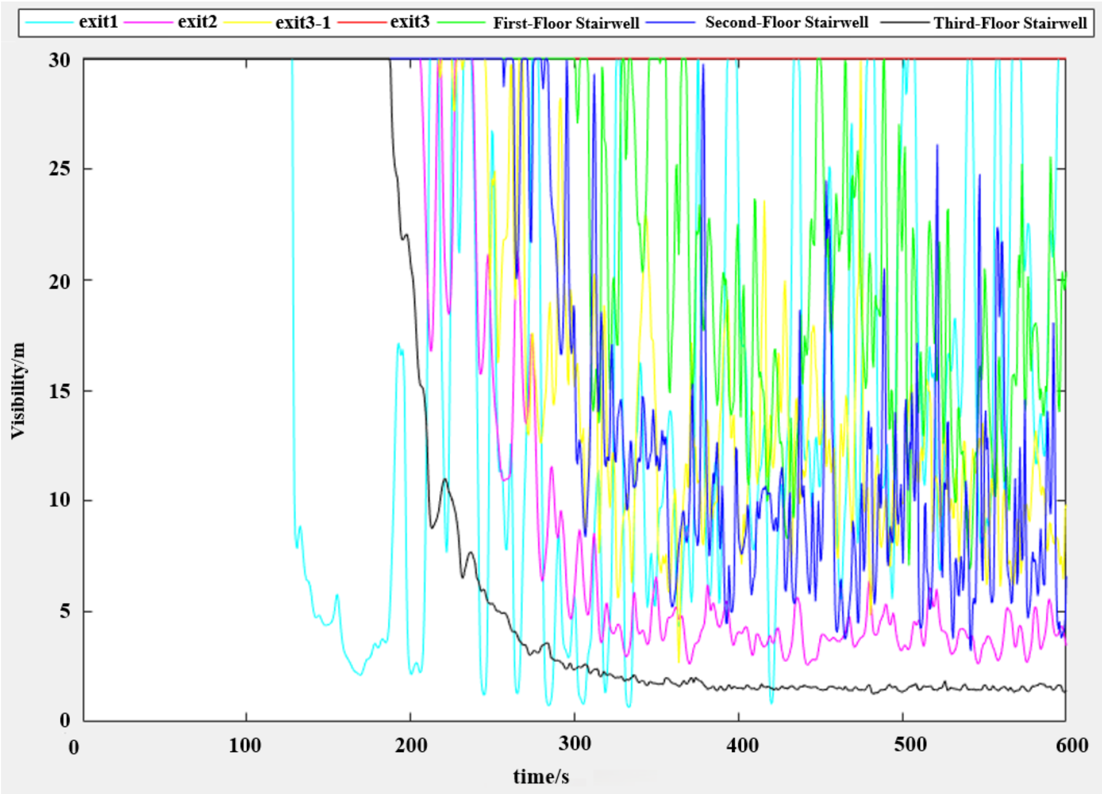

Figure 7. Visibility change curve for Scenario 2

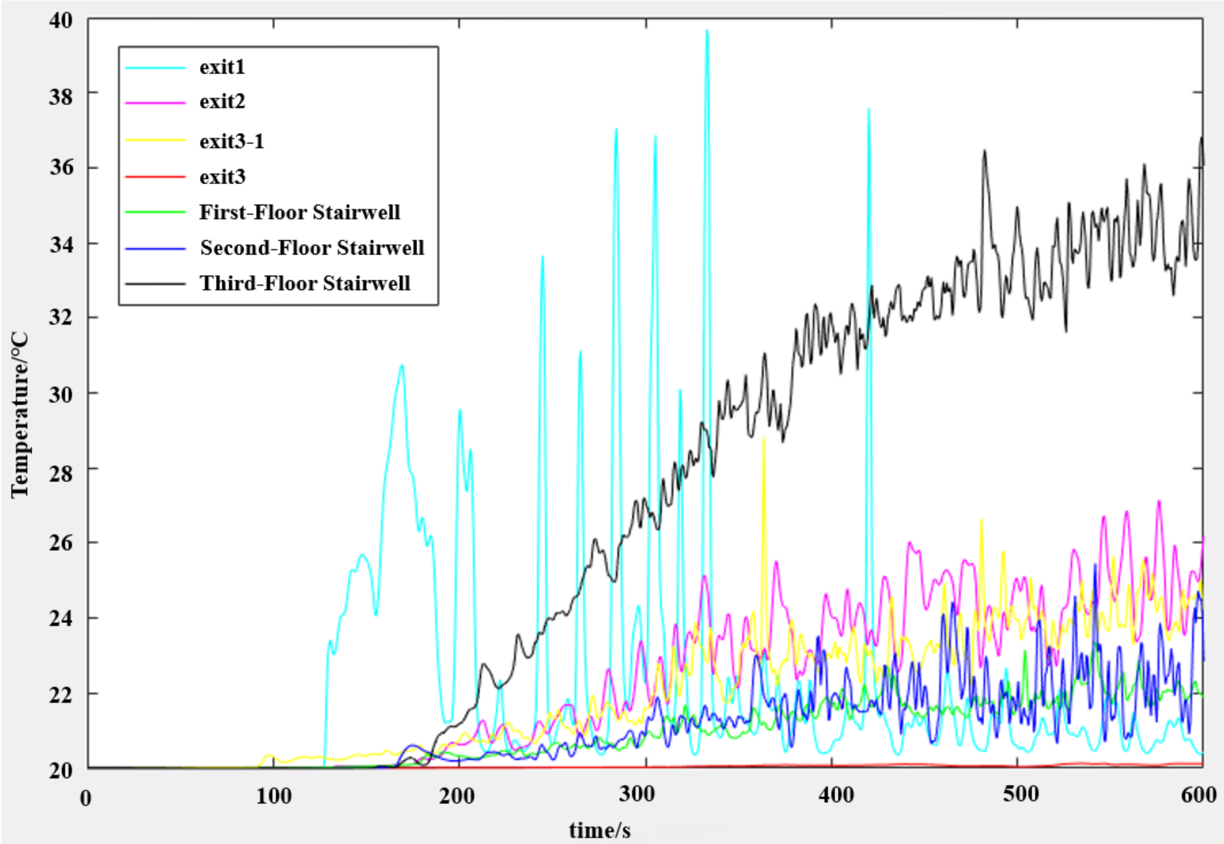

Figure 8. Temperature variation curve for Scenario 2

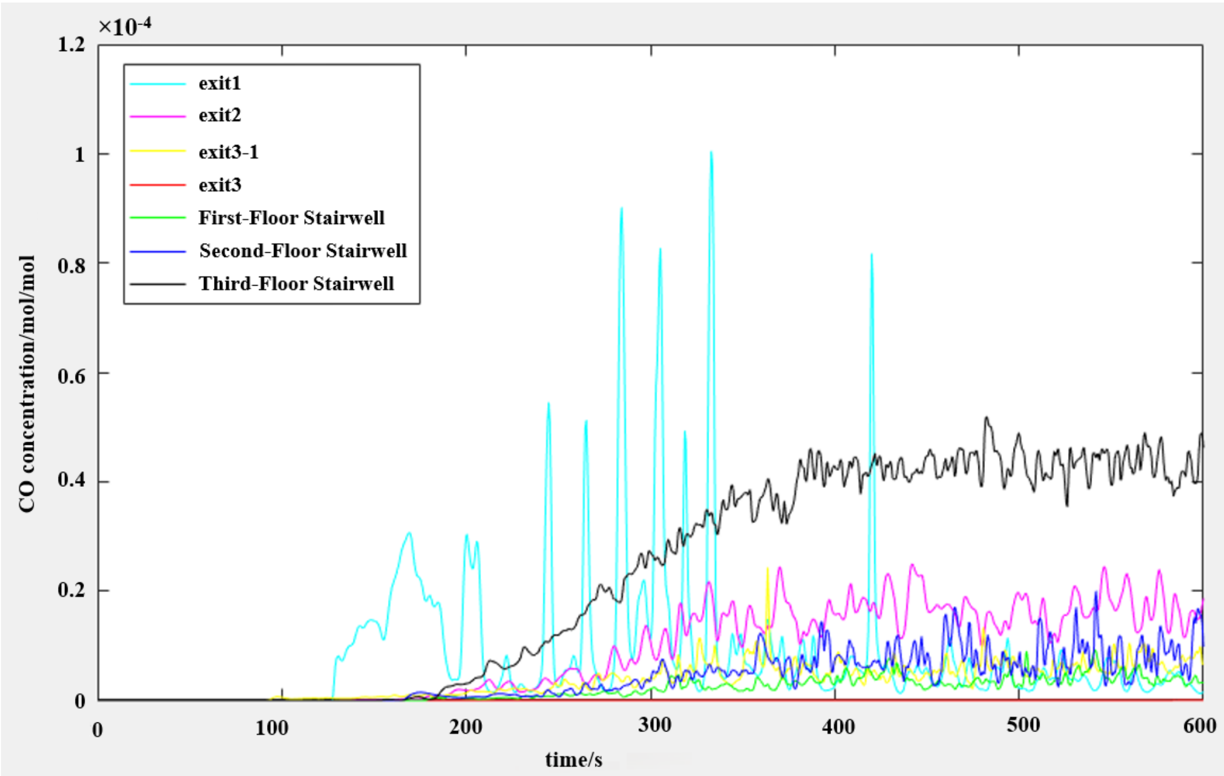

Figure 9. CO concentration variation curve for Scenario 2

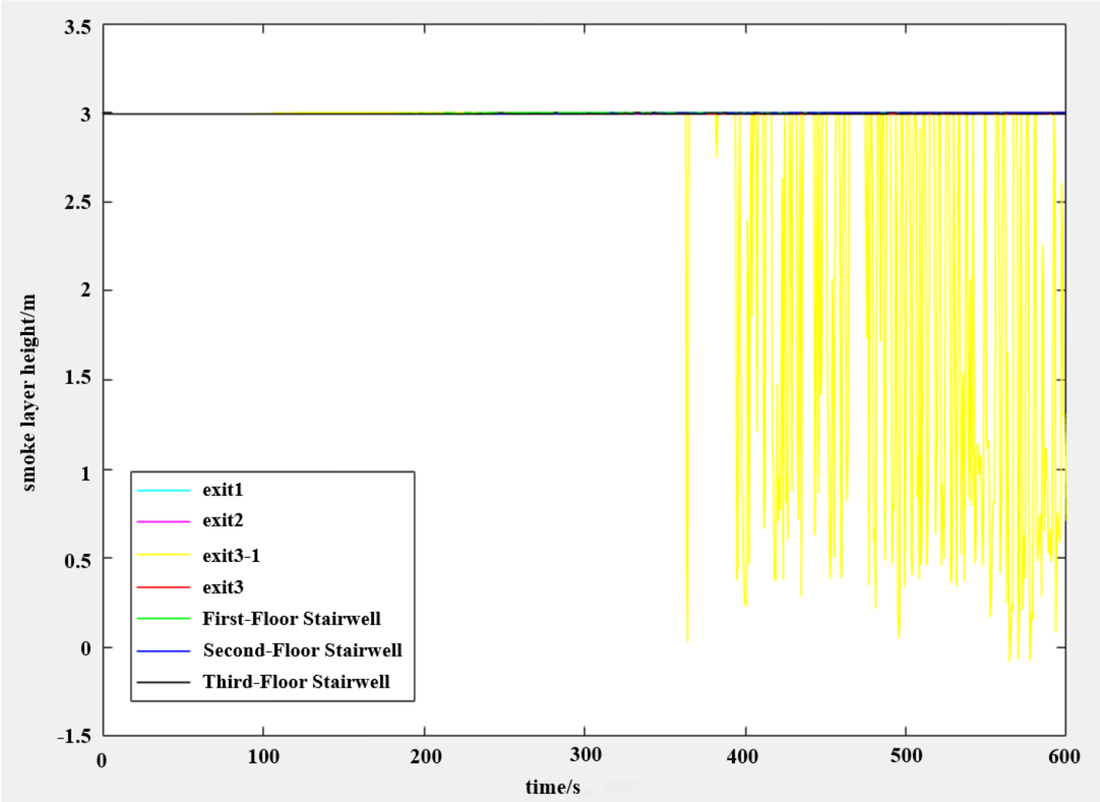

Figure 10. Smoke layer height variation curve for Scenario 2

3.6 Fire Simulation Results for Scenario 3

The visibility, CO concentration, temperature, and smoke layer height variation curves for Scenario 3 are shown in Figures 11 to 14.

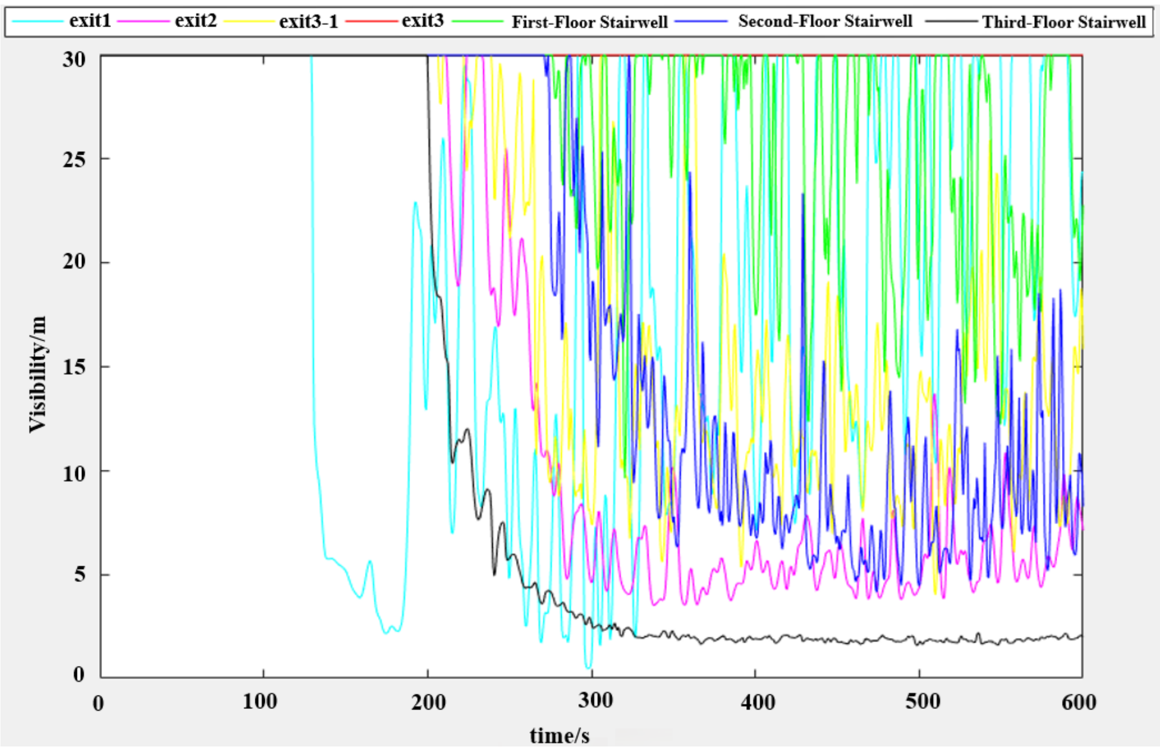

Figure 11. Visibility change curve for Scenario 3

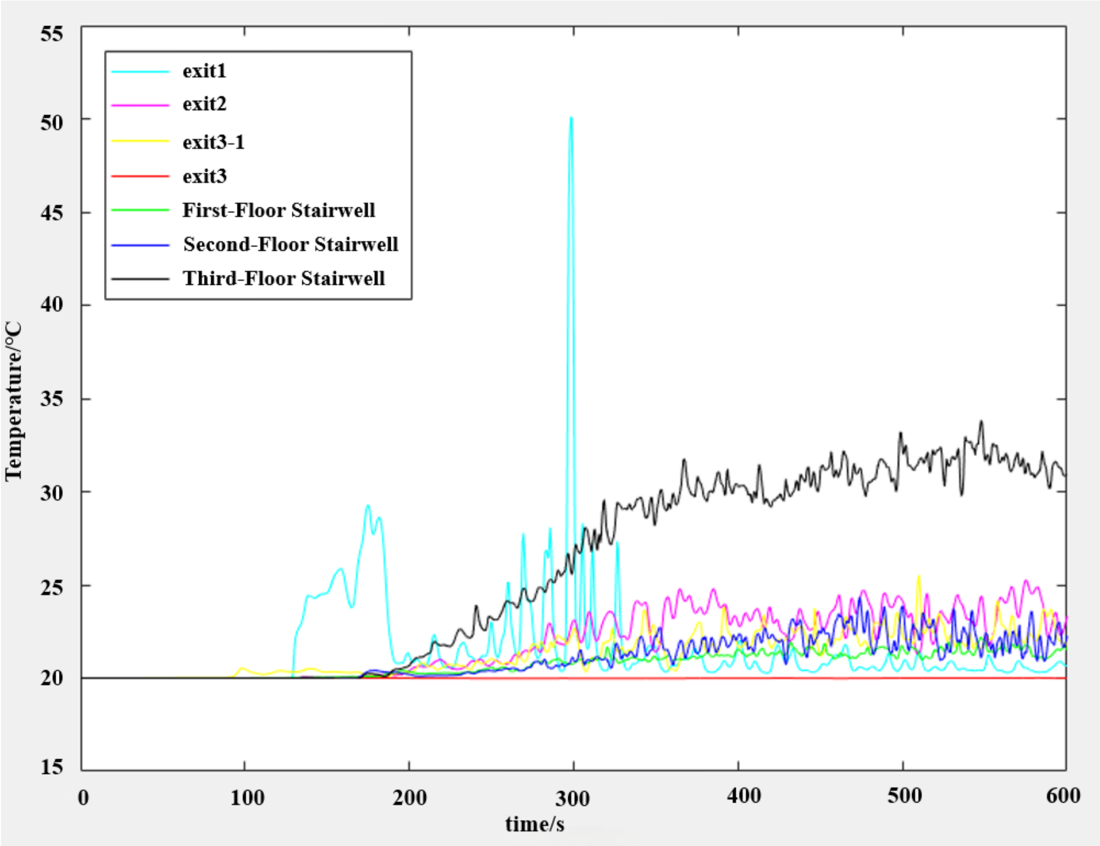

Figure 12. Temperature variation curve for Scenario 3

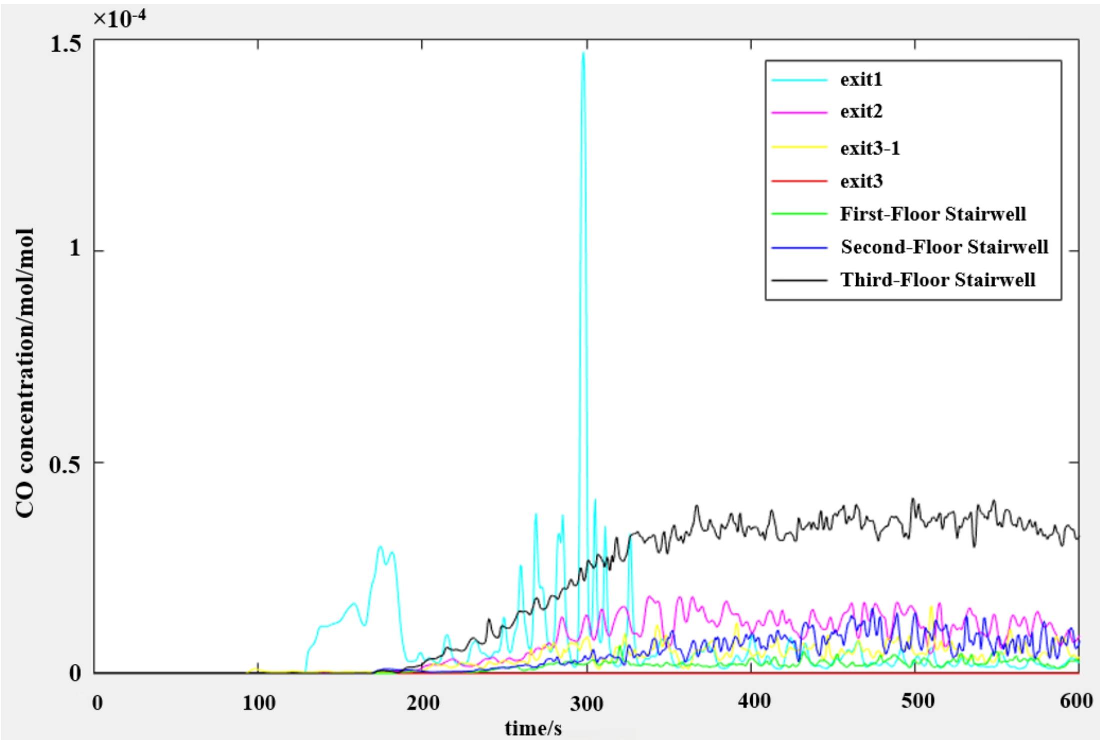

Figure 13. CO concentration variation curve for Scenario 3

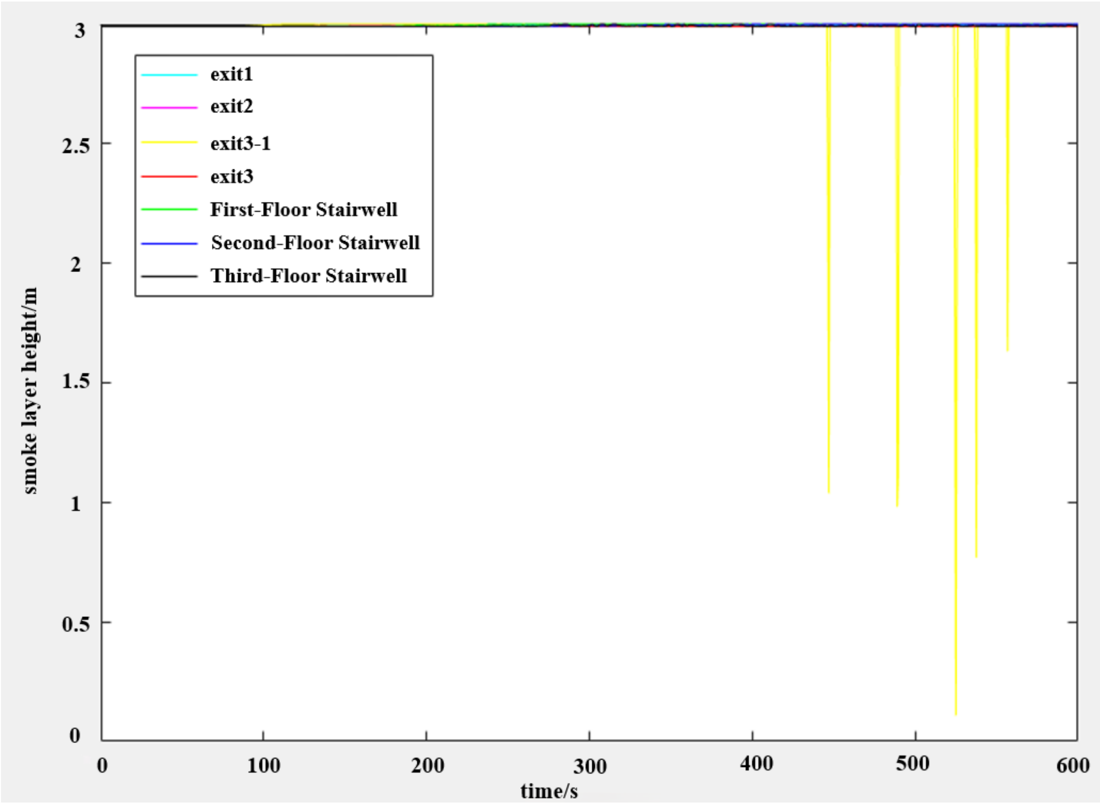

Figure 14. Smoke layer height variation curve for Scenario 3

4 Results and Discussion

4.1 Fire Risk Impact Factor Analysis Based on OPA

From Table 8, it can be observed that among the five dimensions of personnel, building, equipment, environmental, and management factors, the weight of equipment factors is the highest, reaching 0.34. This not only reflects the experts' recognition of the critical role of fire protection facilities in fire prevention and emergency response but also highlights the importance placed on the fire risks that can arise from the aging and quality issues of electrical equipment. Firefighting facilities, such as sprinkler systems, emergency lighting, and fire detection and alarm devices, are the first line of defense when a fire occurs, and electrical equipment, as an indispensable part of daily life and industrial production, directly relates to fire hazards. Therefore, the experts' emphasis on these two types of equipment underscores the need for regular inspection and maintenance of fire protection facilities and strict quality control and timely updates of electrical equipment in fire risk management. The weight of management factors is the lowest, at only 0.05. This may be because, with the widespread dissemination of fire safety knowledge and the strict enforcement of fire regulations, many basic safety management measures are considered standard operating procedures and thus may be taken for granted in the fire risk analysis of employee dormitory buildings, making them less significant in weight allocation compared to more direct fire risk factors. Moreover, the effectiveness of management measures may be more difficult to quantify, and experts may tend to favor factors that can be measured through specific data or tangible results in the assessment. At the same time, the effectiveness of management factors largely depends on the implementation of personnel and equipment factors; if these are well-controlled, the weight of management factors may be relatively reduced.

Through the analysis of Table 8, it can also be observed that the weights of firefighting facility conditions (S_{12}) and the ventilation conditions in the dormitory building (S_{10}) are the highest, at 0.233 and 0.150, respectively. The high weights of these two factors reflect the experts' emphasis on emergency preparedness for fires and fire control capabilities. Firefighting facilities are the first line of defense when a fire occurs, and their condition directly relates to the ability to quickly and effectively control the fire situation, reducing casualties and property damage. Therefore, experts consider the condition of firefighting facilities as a key factor and assign it a higher weight. Similarly, good ventilation conditions help control the spread of smoke, creating favorable conditions for personnel evacuation and fire extinguishing, which is why it also receives a high weight. Following closely behind are the weights of employees' misuse of high-power electrical equipment (S_2) and employee smoking behavior (S_1), which are also relatively high at 0.138 and 0.123, respectively. The higher weights of these two factors reveal the importance of human behavior in the fire risk. These behaviors increase the likelihood of fires, especially in densely populated dormitory environments where a small oversight can lead to serious consequences. Therefore, experts emphasize the management of these high-risk behaviors to reduce fire risks.

Additionally, it can be noticed that the fire emergency plan (S_{15}) has the lowest weight, at only 0.009. This result may be because, although emergency plans are crucial when a fire occurs, they may not be considered an active or continuous point of focus in daily work, thus receiving a lower weight in risk analysis. Furthermore, the effectiveness of emergency plans may be difficult to quantify as they involve preventive measures and response processes rather than direct physical protective measures. Experts may be more inclined to assign higher weights to factors that can be directly observed and measured. However, this does not mean that emergency plans are unimportant; on the contrary, an effective emergency plan can quickly mobilize resources when a fire occurs, reducing losses. Secondly, the rectification of identified issues (S_{14}) has a weight of 0.019, also at a lower level, indicating that rectification in fire risk management may not receive enough attention. This may be because the effectiveness of rectification measures is not as immediate as preventive measures, or the urgency of rectification is not fully recognized. However, timely rectification is crucial for eliminating fire hazards. Therefore, there is a need to strengthen the supervision and implementation of rectification measures.

4.2 Analysis of Fire Scenario Simulation Results

(a) Analysis of Scenario 1

As shown in Figure 3, at the first safety exit (Exit 1), visibility dropped immediately from 30 meters to below 10 meters around 130 seconds after the fire started, and then fluctuated significantly between 1 meter and 30 meters until 600 seconds. Visibility became intermittently high and low. Thus, it can be concluded that after approximately 134 seconds, people could no longer evacuate through the first safety exit. At the security room entrance, which is on the east side of the corridor (Exit 3-1), visibility began to decrease around 240 seconds after the fire started and continued to decline, falling below 10 meters after about 268 seconds. Therefore, it can be concluded that after 268 seconds, the east side of the corridor became impassable, meaning that evacuation to the security room and through the third safety exit (Exit 3) was no longer possible. Although visibility at the third safety exit (Exit 3) was almost unaffected, after about 268 seconds, the security room entrance became unsafe to pass due to visibility issues, which also means that the third safety exit lost its evacuation capability.

From Figure 4, it can be seen that the temperature at the first safety exit (Exit 1) suddenly rose to around 40℃ at about 270 seconds, then returned to around 20℃ after a while. Although the temperature fluctuated significantly a few times, the duration was too short to be considered, and the temperature at the first safety exit did not exceed the dangerous critical value. Therefore, it was safe to pass. The temperature at the third-floor stairwell began to rise gradually around 180 seconds after the fire started, increasing from 20℃ to 39℃ by 600 seconds, but throughout the entire combustion process, the temperature did not exceed the dangerous critical value. Therefore, it was safe to pass.

As shown in Figure 5, the CO concentration at the first safety exit (Exit 1) slightly increased around 120 seconds, then decreased back to approximately $0.2*10^{-4}$ mol/mol after a period. Until 600 seconds, the CO concentration remained basically stable below the dangerous critical value. Therefore, it was safe to pass. The CO concentration at the third-floor stairwell began to rise gradually around 190 seconds after the fire started, increasing from 0 mol/mol to $0.5*10^{-4}$ mol/mol by 600 seconds, but throughout the entire combustion process, the CO concentration did not exceed the dangerous critical value. Therefore, it was safe to pass.

From Figure 6, it can be observed that the smoke layer height at the security room entrance, which is on the east side of the corridor (Exit 3-1), dropped sharply to below 2 meters around 300 seconds, but due to the short duration, it can be disregarded. Then, around 322 seconds, the smoke layer height dropped to below 2 meters again, and from then until 600 seconds, the smoke layer height remained basically below 2 meters with continuous changes. Therefore, it can be concluded that after 322 seconds into the fire, the east side of the corridor, including the security room entrance, became unsafe to pass, which also means that the third safety exit lost its evacuation capability at that time.

(b) Analysis of Scenario 2

As shown in Figure 7, visibility at the first safety exit (Exit 1) dropped sharply around 130 seconds after the fire started, and remained below 10 meters until 600 seconds. Although there were several instances where visibility exceeded 10 meters, the duration was too short to be considered, and thus can be disregarded. In summary, it can be concluded that the first safety exit was not safe to pass after 130 seconds into the fire. Visibility at the second safety exit (Exit 2) generally showed a declining trend, dropping below 10 meters after approximately 278 seconds and continuing to decrease, eventually stabilizing below 5 meters. Therefore, it can be concluded that the second safety exit was not safe to pass after 278 seconds. The visibility at the second-floor stairwell dropped below 10 meters around 357 seconds, being considered unsafe to pass after 343 seconds. The visibility at the third-floor stairwell dropped to around 10 meters at about 227 seconds and then continued to decrease, stabilizing at around 2 meters, making it impassable after approximately 227 seconds.

From Figure 8, it can be observed that the temperature at the first safety exit (Exit 1) suddenly rose around 130 seconds, increasing from 20℃ to around 23℃, and then remained relatively stable at around 21℃. The highest temperature at the first safety exit reached only about 40℃, which did not exceed the dangerous critical value, making it safe to pass. The temperature at the third-floor stairwell began to rise around 200 seconds and continued to increase over time but did not reach the dangerous critical value, making it safe to pass.

As shown in Figure 9, the CO concentration at the first safety exit (Exit 1) slightly increased around 130 seconds and continued to rise until about 210 seconds, reaching a maximum of $0.3*10^{-4}$ mol/mol. After that and until 600 seconds, the CO concentration remained basically below the dangerous critical value, making it safe to pass. The CO concentration at the third-floor stairwell began to rise gradually around 195 seconds after the fire started, increasing from 0 mol/mol to about $0.4*10^{-4}$ mol/mol by 600 seconds, but throughout the entire combustion process, the CO concentration did not exceed the dangerous critical value, making it safe to pass.

From Figure 10, it can be observed that the smoke layer height at the security room entrance, which is on the east side of the corridor (Exit 3-1), dropped sharply below 2 meters around 364 seconds, but due to the short duration, it can be disregarded. Then, around 395 seconds, the smoke layer height dropped below 2 meters again, and from then until 600 seconds, the smoke layer height continuously fluctuated between 0 meters and 3 meters with significant changes. Therefore, it can be concluded that the east side of the corridor, including the security room entrance, was not safe to pass after 395 seconds into the fire, which also implies that the third safety exit lost its evacuation capability at that time.

(c) Analysis of Scenario 3

As shown in Figure 11, visibility at the first safety exit (Exit 1) dropped sharply around 133 seconds, decreasing from 30 meters to approximately 5 meters. After a while, it suddenly recovered to above 10 meters, but due to the short duration, this can be disregarded. Until around 375 seconds, visibility at the first safety exit fluctuated below 10 meters, with a few instances where visibility exceeded 10 meters, but these were too brief to be considered. After approximately 375 seconds, visibility at the first safety exit generally stabilized above 10 meters. Therefore, it can be concluded that the first safety exit was safe to pass from 0-133 seconds after the start of the fire and after 375 seconds; during other times, visibility issues impaired its safe evacuation function. The visibility at the third-floor stairwell dropped to around 10 meters at about 227 seconds and then continued to decrease, stabilizing at around 2 meters, making the third-floor stairwell impassable after approximately 227 seconds.

From Figure 12, it can be observed that the temperature at the first safety exit (Exit 1) suddenly increased around 133 seconds and continued to rise until around 190 seconds, reaching a maximum temperature of 30℃. After that, the temperature remained relatively stable between 20℃ and 30℃, with the highest temperature at the first safety exit only reaching around 50℃, which did not exceed the dangerous critical value. Therefore, the first safety exit was safe to pass. The temperature at the third-floor stairwell began to rise around 195 seconds and continued to increase over time, reaching a maximum of approximately 34℃ by 600 seconds, but it did not reach the dangerous critical value, making it safe to pass.

As shown in Figure 13, the CO concentration at the first safety exit (Exit 1) slightly increased around 135 seconds, followed by a significant increase between 260 seconds and 320 seconds, reaching a maximum of $1.5*10^{-4}$ mol/mol. After a period, the CO concentration dropped to around $0.5*10^{-4}$ mol/mol and remained relatively stable at this level until 600 seconds. Throughout the entire combustion process, the CO concentration did not exceed the dangerous critical value, making it safe to pass. The CO concentration at the third-floor stairwell began to rise gradually around 190 seconds after the fire started, increasing from 0 mol/mol to around $0.4*10^{-4}$ mol/mol by 600 seconds. However, throughout the entire combustion process, the CO concentration did not exceed the dangerous critical value, making it safe to pass.

From Figure 14, it can be seen that the smoke layer height at the security room entrance, which is on the east side of the corridor (Exit 3-1), remained relatively stable at around 3 meters within 600 seconds after the fire started. Although there were several significant drops in the smoke layer height between 400 seconds and 600 seconds, with each drop going below 2 meters, the duration of these drops was too short to be considered significant. Therefore, it can be concluded that the smoke layer height had almost no impact on the safe passage capacity at the security room entrance and the east side of the corridor during the fire.

By analyzing the smoke layer height, CO concentration, temperature, and visibility in the three safety exits, the east side of the first-floor corridor, and the three stairwells across the three scenarios, the times at which access to each area is prohibited were determined, as shown in Table 11.

From Table 11, it can be seen that in Scenario 1, due to the impact of visibility, the first safety exit (Exit 1) became impassable after 134 seconds; the second safety exit (Exit 2) after 297 seconds; the third safety exit (Exit 3) after 268 seconds; the first-floor stairwell between 494 and 536 seconds; the second-floor stairwell after 343 seconds; and the third-floor stairwell after 218 seconds. Due to the influence of smoke layer height, the third safety exit (Exit 3) became impassable after 322 seconds. In summary, the available safe evacuation time for the entire building in Scenario 1 was 218 seconds. In Scenario 2, due to the impact of visibility, the first safety exit (Exit 1) became impassable after 130 seconds; the second safety exit (Exit 2) after 278 seconds; the third safety exit (Exit 3) after 325 seconds; the second-floor stairwell after 357 seconds; and the third-floor stairwell after 227 seconds. Due to the influence of smoke layer height, the third safety exit (Exit 3) became impassable after 395 seconds. In summary, the available safe evacuation time for the entire building in Scenario 2 was 227 seconds. In Scenario 3, due to the impact of visibility, the first safety exit (Exit 1) was impassable between 133 and 375 seconds; the second safety exit (Exit 2) after 281 seconds; the third safety exit (Exit 3) after 290 seconds; the second-floor stairwell after 394 seconds; and the third-floor stairwell after 227 seconds. In summary, the available safe evacuation time for the entire building in Scenario 3 was 227 seconds.

Table 11. Prohibited passage time for each area in different scenarios

Scenario	Area	Time Prohibited for Passage(s) by Factor			
		Visibility (m)	Temperature (°C)	CO Concentration (mol/mol)	Smoke Layer Height (m)
Scenario 1	First safety exit (Exit 1)	134	—	—	—
	Second safety exit (Exit 2)	297	—	—	—
	Third safety exit (Exit 3)	268	—	—	322
	Security room entrance on the east side of the corridor (Exit 3-1)	268	—	—	322
	First-floor stairwell	494-536	—	—	—
	Second-floor stairwell	343	—	—	—
	Third-floor stairwell	218	—-	—	—-
Scenario 2	First safety exit (Exit 1)	130	—	—	—
	Second safety exit (Exit 2)	278	—	—	—
	Third safety exit (Exit 3)	325	—	—	395
	Security room entrance on the east side of the corridor (Exit 3-1)	325	—	—	395
	First-floor stairwell	—	—	—	—
	Second-floor stairwell	357	—	—	—
	Third-floor stairwell	227	—	—	—
Scenario 3	First safety exit (Exit 1)	133-375	—	—	—
	Second safety exit (Exit 2)	281	—	—-	—
	Third safety exit (Exit 3)	290	—	—	—
	Security room entrance on the east side of the corridor (Exit 3-1)	290	—	—	—
	First-floor stairwell	—	—	—	—
	Second-floor stairwell	394	—	—	—
	Third-floor stairwell	227	—	—	—

Comparing Scenarios 2 and 3 with Scenario 1, it can be observed that opening the windows at both ends of the corridors in the employee dormitory building (natural ventilation) and adding an automatic sprinkler system can significantly inhibit the spread of fire. Firstly, in terms of available safe evacuation time, both Scenario 2 and Scenario 3 have longer available safe evacuation time than Scenario 1. Secondly, examining the variation curves of visibility, temperature, and other factors, increased ventilation and the addition of a sprinkler system have played a significant role in smoke exhaust and temperature reduction.

By comparing Scenario 2 and Scenario 3, it can be found that the suppression effect of adding an automatic sprinkler system on the fire is slightly stronger than that of opening the windows at both ends of the building's corridors (natural ventilation). Firstly, although the available safe evacuation time for the entire building in Scenario 2 and Scenario 3 is the same, as shown in Table 11, the available evacuation time for the third safety exit in Scenario 2 is slightly greater than in Scenario 3, while the available evacuation times for other areas, such as the first and second safety exits, are slightly less in Scenario 2 than in Scenario 3. Secondly, looking at the variation curves of temperature, CO concentration, and smoke layer height, the overall levels of temperature and CO concentration in all areas in Scenario 3 are slightly lower than in Scenario 2. Moreover, in Scenario 3, the smoke layer height did not significantly affect the available evacuation time for any area, whereas in Scenario 2, the smoke layer height impacted the available evacuation time at the security room entrance, which is on the east side of the corridor (Exit 3-1), and consequently, it also affected the available evacuation time for the third safety exit (Exit 3).

In Sections 3.1 and 3.2 of this study, after constructing the fire risk impact factor indicator system for the employee dormitory building, the OPA was applied to determine the weights of each impact factor indicator. The result showed that the weight of the firefighting facility condition (S_{12}) is greater than that of the dormitory's ventilation condition (S_{10}). In this section, the conclusion drawn is that the suppression effect of adding an automatic sprinkler system on the fire is slightly stronger than that of ventilating by opening the windows at both ends of the building's corridors. From this, it can be inferred that the fire risk analysis results for the employee dormitory building are reliable.

4.3 Expert Interviews Based on Fire Simulation Results

To validate the accuracy of the fire simulation results and enhance their practical application value, this study invited three experts with many years of experience in fire accident investigation and fire safety assessment from the local fire rescue brigade for in-depth interviews. These experts, based on their extensive experience in fire dynamics, safety design, and accident investigation, provided objective evaluations of the research findings presented in the simulation results. The experts acknowledged the significant impact of the rapid decrease in visibility within the building during a fire, as shown in the simulation results, which is consistent with what they had observed in actual fire accidents. At the same time, the experts agreed with the simulation's depiction of the effects of natural ventilation and automatic sprinkler systems in suppressing the fire, noting that these measures have been proven effective in practical applications to slow the spread of fires and reduce the threat of fire to personnel safety. Furthermore, the experts suggested incorporating more human behavior variables in future simulation studies, such as the diversity of evacuation behaviors and response time to fire alarms, to enhance the realism and predictive accuracy of the simulations. These variables can make the simulation results more reflective of the actual dynamics of personnel evacuation in fire situations, thereby enhancing the utility and precision of the simulation model. The feedback from the experts not only confirmed the relevance of the simulation results but also provided valuable guidance for further improvement of the simulation model.

5 Conclusion and Outlook

This study conducted an in-depth analysis of fire risks in employee dormitory buildings, selecting a specific employee dormitory as a case study. The OPA was applied to determine the relative importance of fire risk impact factors, and fire scenario simulation technology was utilized to simulate the role and the impact of some factors in actual fire events. The study not only provides a scientific basis for the fire safety management of dormitory buildings but also helps managers identify and prioritize key fire risk factors, thus more effectively allocating resources to improve fire safety conditions. Through fire scenario simulation, this study enhances the understanding of fire development dynamics, which is crucial for formulating fire emergency response strategies and improving fire control capabilities during fires. Additionally, the simulation results validate the accuracy of the fire risk analysis results obtained by the OPA, providing a more reliable scientific basis for fire safety management in dormitory buildings.

This study identified the fire risk impact factor indicator system for employee dormitory buildings through literature research and field interviews. Subsequently, the weights of each impact factor indicator were determined using the OPA. The results indicated that the condition of firefighting facilities, the ventilation of the dormitory building, the behavior of employees misusing high-power electrical equipment, and employee smoking behavior are relatively important factors. The identification of these key factors not only provides a clear focus for fire prevention in dormitory buildings but also emphasizes the importance of taking preventive measures in these areas. By optimizing firefighting facilities and improving ventilation conditions, the spread of fire can be more effectively controlled in the event of a fire, ensuring the safety of residents. At the same time, this highlights the necessity of safety education for employees, especially in managing and intervening in the misuse of electrical appliances and smoking behaviors, to reduce fire risks caused by human factors.

Based on the PyroSim fire numerical simulation software, different fire scenarios were set for the two most influential factors with the largest weight proportions. The simulation results revealed that among the factors of temperature, visibility, CO concentration, and smoke layer height, visibility is the primary factor affecting the available safe evacuation time. Additionally, the roles of natural ventilation and firefighting facilities, particularly the effects of automatic sprinkler systems, were compared in the fire simulation. It was found that while natural ventilation helps to some extent in suppressing the spread of fire, automatic sprinkler systems are more significant in controlling the fire and extending the safe evacuation time. These simulation results hold significant importance for practical fire safety management. They not only provide guidance to prioritize the configuration and maintenance of key firefighting facilities in building fire protection design but also highlight the need to pay special attention to the impact of visibility on evacuation efficiency when formulating evacuation plans, thereby quickly and effectively guiding the evacuation of personnel in the early stages of a fire. Furthermore, these findings aid in considering the layout of windows and optimization of ventilation systems during the architectural design phase to enhance the natural ventilation effect during a fire. Applying these research outcomes in practice can significantly improve the level of fire safety in buildings and reduce the potential damage caused by fires.

Based on the risk analysis and scenario simulation results, the following recommendations were proposed for the fire safety management of employee dormitory buildings:

(a) The standards of firefighting facilities could be enhanced. The scenario simulation results highlight the importance of automatic sprinkler systems in controlling the spread of fire and buying time for evacuation, while also emphasizing the significant impact of visibility on available safe evacuation time. It is recommended that the dormitory building should install and maintain automatic sprinkler systems and ensure that every area is equipped with effective fire alarms and emergency lighting. This requires an initial investment. But in the long term, it can significantly improve the ability to respond to fires, reduce casualties and property loss caused by fires, and enhance the market value of the building.

(b) The natural ventilation system could be improved. The simulation shows that natural ventilation can suppress the spread of fire to a certain extent, but its effects are limited. It is recommended to optimize the natural ventilation system of the dormitory building, e.g., adding more ventilation windows or adjusting the layout of windows to facilitate the expulsion of smoke. This is relatively easy to implement and has a low cost, mainly involving architectural design adjustments and the installation of ventilation facilities. Such improvements can not only enhance visibility during a fire, reducing the obstruction of smoke to evacuation, but also improve the comfort of the living environment.

(c) Fire safety education and training could be strengthened. Human factors, such as the misuse of electrical appliances and smoking behavior, are significant contributors to fire risks. It is recommended to regularly conduct fire safety training and drills for employees, especially focusing on safety education regarding smoking and the use of electrical appliances. This measure is relatively simple to implement and has a low cost, but it can significantly improve employees' safety awareness and their ability to self-rescue and assist others in the event of a fire.

Although this study has achieved certain results in analyzing the fire risks of employee dormitory buildings and conducting scenario simulations, it has some limitations. Firstly, the constructed fire risk factor indicator system may not cover all influencing factors comprehensively, and the study object is limited to a specific dormitory building case, which restricts the broad applicability of the results. Secondly, the scenario simulation focuses only on fire simulation and does not consider factors related to human evacuation, which may lead to an underestimation of actual fire emergency response capabilities. Lastly, the parameter settings used in the scenario simulation process rely on theoretical values and empirical estimates, while actual fire situations are usually more complex, potentially leading to discrepancies between simulation results and real situations. Based on these limitations, future research could consider expanding the coverage of the indicator system, increasing case analyses of different types of employee dormitory buildings, incorporating simulations of human evacuation, and integrating more actual data into parameter settings to enhance the comprehensiveness and accuracy of the research.

Author Contributions

Qiang Li: Methodology, Data curation, Writing-Original Draft.
Zaohong Zhou: Conceptualization, Writing-Review & Editing.
Yunbin Sun: Fire simulation.
Hongjun He: Expert interviews and on-site interviews.

Funding

This work was supported by the National Social Science Fund Project (Grant No.: 20BJY144), National Natural Science Foundation of China (Grant No.: 72361013), Science and Technology Project of Jiangxi Provincial Department of Education (Grant No.: GJJ2200530).

Data Availability

Data will be made available on request.

Conflicts 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.

References

[1] S. D. Griffiths, J. A. Entwistle, F. J. Kelly, and M. E. Deary, "Characterising the ground level concentrations of harmful organic and inorganic substances released during major industrial fires, and implications for human health," *Envir. Int.*, vol. 162, p. 107152, 2022. https://doi.org/10.1016/j.envint.2022.107152

[2] L. Wang, W. Li, W. Feng, and R. Yang, "Fire risk assessment for building operation and maintenance based on BIM technology," *Build. Environ.*, vol. 205, p. 108188, 2021. https://doi.org/10.1016/j.buildenv.2021.108188

[3] M. A. Hassanain, M. A. Hafeez, and M. O. Sanni-Anibire, "A ranking system for fire safety performance of student housing facilities," *Safety Sci.*, vol. 92, pp. 116–127, 2017. https://doi.org/10.1016/j.ssci.2016.10.002

[4] F. Khajehnasiri, V. Zaroushani, and Z. B. Haris, "Fire risk analysis in a student dormitory using fire risk index method for multistorey apartment buildings in 2021: A case study," *J. Health & Safety at Work*, vol. 13, no. 1, pp. 90–108, 2023.

[5] M. Zhang and W. J. Yu, "Analysis and research on fire safety of university dormitory based on Bayesian network," in *2021 IEEE 12th International Conference on Software Engineering and Service Science (ICSESS)*, Beijing, China, 2021, pp. 295–299. https://doi.org/10.1109/ICSESS52187.2021.9522247

[6] X. Long, X. Zhang, and B. Lou, "Numerical simulation of dormitory building fire and personnel escape based on Pyrosim and pathfinder," *J. Chin. Inst. Eng.*, vol. 40, no. 3, pp. 257–266, 2017. https://doi.org/10.1080/02533839.2017.1300072

[7] R. Tabaczenski, C. Corrêa, T. Ancelmo Pires, and J. J. Silva, "Numerical simulation and fire experiment in residential dormitory," *Rev. ALCONPAT*, vol. 9, no. 1, pp. 15–29, 2019. http://doi.org/10.21041/ra.v9i1.315

[8] H. Hostetter and M. Z. Naser, "Characterizing egress components for wheelchair users in dormitory building fires," *Nat. Hazards Res.*, vol. 4, no. 1, pp. 173–186, 2024. https://doi.org/10.1016/j.nhres.2023.11.012

[9] P. Wang, H. Dai, X. Yu, Q. Wang, S. Li, and C. Jia, "Fire-spread characteristics and evacuation plan optimization of old style multi-story student apartments," *Fire*, vol. 7, no. 3, p. 72, 2024. https://doi.org/10.3390/fire7030072

[10] Y. Huang, Z. Guo, H. Chu, and R. Sengupta, "Evacuation simulation implemented by ABM-BIM of unity in students' dormitory based on delay time," *ISPRS Int. J. Geo-Inf.*, vol. 12, no. 4, p. 160, 2023. https://doi.org/10.3390/ijgi12040160

[11] S. D. Jeon, J. Y. Lee, and H. S. Kong, "Evaluation of fire and evacuation safety in school dormitories," *J. Korean Soc. Hazard Mitig.*, vol. 24, no. 4, pp. 139–149, 2024. https://doi.org/10.9798/KOSHAM.2024.24.4.139

[12] S. Zhao, A. Hendalianpour, and P. Liu, “Blockchain technology in omnichannel retailing: A novel fuzzy large-scale group-DEMATEL & Ordinal Priority approach,” *Expert Syst. Appl.*, vol. 249, p. 123485, 2024. https://doi.org/10.1016/j.eswa.2024.123485

[13] Y. Ataei, A. Mahmoudi, M. R. Feylizadeh, and D. F. Li, “Ordinal priority approach (OPA) in multiple attribute decision-making,” *Appl. Soft Comput.*, vol. 86, p. 105893, 2020. https://doi.org/10.1016/j.asoc.2019.105893

[14] A. Mahmoudi and S. A. Javed, “Strict and weak ordinal relations for estimating the criteria weights in Ordinal Priority Approach (OPA),” *MethodsX*, vol. 11, p. 102389, 2023. https://doi.org/10.1016/j.mex.2023.102389

[15] D. Pamucar, M. Deveci, I. Gokasar, L. Martínez, and M. Köppen, “Prioritizing transport planning strategies for freight companies towards zero carbon emission using ordinal priority approach,” *Comput. Ind. Eng.*, vol. 169, p. 108259, 2022. https://doi.org/10.1016/j.cie.2022.108259

[16] H. Zhang, Z. H. Miao, H. N. Lv, and Z. L. Leng, “Evacuation simulation of large theater based on Pyrosim and Pathfinder,” *J. Phys. Conf. Ser.*, vol. 2289, no. 1, p. 012017, 2022. https://doi.org/10.1088/1742-6596/2289/1/012017

[17] Y. Zhang, R. Tian, L. Peng, X. Yu, and Y. Wang, “Fire safety resilience assessment of residential self-built houses according to the TOPSIS method,” *Sustainability*, vol. 15, no. 16, p. 12417, 2023. https://doi.org/10.3390/su151612417

[18] Y. Wang, R. Zheng, and M. Li, “Risk assessment of fire safety in large-scale commercial and high-rise buildings based on intuitionistic fuzzy and social graph,” *J. Build. Eng.*, vol. 89, p. 109165, 2024. https://doi.org/10.1016/j.jobe.2024.109165

[19] F. Liu, S. Zhao, M. Weng, and Y. Liu, “Fire risk assessment for large-scale commercial buildings based on structure entropy weight method,” *Safety Sci.*, vol. 94, pp. 26–40, 2017. https://doi.org/10.1016/j.ssci.2016.12.009

[20] G. F. Marantika, M. A. Rohman, F. Rachmawati, and I. P. A. Wiguna, “Identification of fire safety indicators for shopping centre buildings in Surabaya,” *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 930, no. 1, p. 012009, 2020. https://doi.org/10.1088/1757-899x/930/1/012009

[21] H. J. Joo, Y. J. Choi, C. Y. Ok, and J. H. An, “Determination of fire risk assessment indicators for building using big data,” *J. Korea Inst. Build. Constr.*, vol. 22, no. 3, pp. 281–291, 2022. https://doi.org/10.5345/JKIBC.2022.22.3.281

[22] J. Zhang, D. Huang, Q. You, J. Kang, M. Shi, and X. Lang, “Evaluation of emergency evacuation capacity of urban metro stations based on combined weights and TOPSIS-GRA method in intuitive fuzzy environment,” *Int. J. Disaster Risk Reduct.*, vol. 95, p. 103864, 2023. https://doi.org/10.1016/j.ijdrr.2023.103864

[23] L. Xu, K. Huang, J. Liu, D. Li, and Y. F. Chen, “Intelligent planning of fire evacuation routes using an improved ant colony optimization algorithm,” *J. Build. Eng.*, vol. 61, p. 105208, 2022. https://doi.org/10.1016/j.jobe.2022.105208

[24] Y. Ma, Z. Zhang, W. Zhang, E. W. Lee, and M. Shi, “Development of a time pressure-based model for the simulation of an evacuation in a fire emergency,” *J. Build. Eng.*, vol. 87, p. 109069, 2024. https://doi.org/10.1016/j.jobe.2024.109069

[25] X. Li, R. Chen, Y. Zhu, and C. Y. Jim, “Emergency fire evacuation simulation of underground commercial street,” *Simul. Model. Pract. Theory*, vol. 134, p. 102929, 2024. https://doi.org/10.1016/j.simpat.2024.102929

[26] Z. Yan, Y. Wang, and L. Chao, “Simulation study on fire and evacuation of super high-rise commercial building,” *Case Stud. Thermal Eng.*, vol. 52, p. 103519, 2023. https://doi.org/10.1016/j.csite.2023.103519