Journal of Engineering Management and Systems Engineering
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Fire Risk Assessment and Simulation of Multi-Functional Teaching Buildings: A Combined Application of DEMATEL and PyroSim

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Received: 01-18-2025 **Revised:** 02-15-2025 **Accepted:** 03-07-2025

Citation: H. J. He, Z. H. Zhou, Y. B. Sun, and Q. Li, "Fire risk assessment and simulation of multi-functional teaching buildings: A combined application of DEMATEL and PyroSim," *J. Eng. Manag. Syst. Eng.*, vol. 4, no. 1, pp. 1–20, 2025. https://doi.org/10.56578/jemse040101.

Abstract: Multi-functional public teaching buildings, as high-density spaces, are subject to significant fire risks due to the large number of occupants and the complex nature of their design. In the event of a fire, the consequences can be catastrophic. Therefore, fire risk assessment is of paramount importance in the design and operation of such buildings. A comprehensive evaluation framework is proposed, integrating the Work Breakdown Structure (WBS) and the Risk Breakdown Structure (RBS) into a unified approach, referred to as the Integrated Work Breakdown Structure and Risk Breakdown Structure (i-WRBS) method. This framework identifies 15 key fire risk factors relevant to public school buildings. The Decision-Making Trial and Evaluation Laboratory (DEMATEL) method is employed to analyze the interrelationships among these factors, while PyroSim fire simulation software is used to model the dynamics of fire smoke propagation under varying wind conditions. The diffusion of smoke in stairwells is simulated under different wind speeds and directions, and the fire risk is evaluated based on the resulting outcomes. The findings indicate that both wind speed and direction play a crucial role in determining the trajectory and velocity of smoke spread, especially within stairwells. Under low wind conditions or in the absence of wind, smoke diffusion is confined to areas close to the fire source, with stairwells located farther from the fire exhibiting comparatively lower risks. However, under higher wind speeds, the speed and range of smoke diffusion are significantly increased, with a pronounced effect in the downwind direction. The fire hazards on higher floors are found to be more sensitive to variations in wind speed, as increased wind velocity leads to more substantial fluctuations in temperature caused by the combustion process. These fluctuations are exacerbated on higher floors. The findings offer valuable insights into fire risk management, contributing to the development of fire safety strategies and the formulation of evacuation plans for large public buildings.

Keywords: Fire risk; Multi-functional teaching buildings; Smoke diffusion; PyroSim; DEMATEL method; Risk assessment; Fire simulation; Wind effects; Evacuation planning; Safety management

1 Introduction

Schools are densely populated environments characterized by diverse architectural designs, with public teaching buildings being particularly prevalent and essential. These buildings are typically large in scale, functionally complex, and subject to a wide range of influencing factors, all while accommodating high levels of occupant mobility. With the frequent occurrence of extreme weather and the deepening of education reform, campus building design is focused on spatial layout. Campus architectural design demonstrates greater flexibility [1] in spatial layout [2], form [3], and other aspects, but the interconnectedness of multifunctionality also brings security risks. In recent years, various types of campus fire accidents have occurred frequently, and multi-functional public teaching buildings have become high-risk areas. The unique characteristics of building fire protection, electrical load management, and spatial design contribute to the heightened risk of fires, which can result in significant harm to groups of individuals, substantial property damage, and other severe consequences. For example, in January 2024, a fire broke out on the third floor of Yingcai School in Yanshanpu Village, Dushu Town, Fangcheng County, Henan Province, China, resulting in multiple deaths; in May, a fire broke out in the auditorium of Minglun Campus of Henan University, causing severe damage. It can be seen that preventing fires in teaching buildings and identifying and responding to fire threats in advance have become important issues in campus safety management. It is crucial to use simulation technology to identify fire patterns, scientifically assess fire risk levels, and propose preventive measures to enhance campus fire prevention and control capabilities. This article will delve into the fire risks of multifunctional public teaching buildings, aiming to provide useful references for campus fire prevention and control.

Extensive research on fire risk assessment and prevention in buildings has been conducted both domestically and internationally. Early studies predominantly employed traditional fire assessment methods, which were largely qualitative or semi-qualitative and semi-quantitative, including fire risk index method [4], fuzzy analytic hierarchy process [5], fuzzy comprehensive evaluation method [6], Delphi method [7], etc. These methods focus on analyzing the fire performance, fire protection facility configuration, disaster causing factors and other indicators of buildings to determine the probability and degree of fire risk. For example, Choi [8] proposed a quantitative risk assessment framework that combines transient event trees and Markov chains to analyze the probability of fire scenarios, and considers the impact of uncertainty factors on consequences. This method takes commercial buildings as an example and compares the assessment results with fire statistical data. With the advancement of technology and the development of computer technology, numerical simulation technology is increasingly widely used in the field of fire, such as reproducing major fire accidents, conducting multi condition analysis of single factors in buildings, etc. Scholars use Building Information Modeling (BIM) technology and fire simulation software (such as Pyrosim and Pathfinder) to conduct multi scenario simulation calculations, study fire deployment [9], indoor firefighter clothing and work safety design [10], alarm system design [11], building design [12], crowd evacuation path optimization [13], and other issues. In terms of fire emergency response, traditional management often adopts reactive fire management methods for sudden fire emergencies, such as using fire extinguishers, firefighters, aerial refueling machines, and other short-term technical solutions to extinguish fires and maintain environmental protection [14]. However, with the intensification of climate change, concerns have emerged regarding the reliance on reactive fire risk assessment methods for conveying fire risk information. As a result, preventive risk analysis has become a focal point of contemporary research. For example, Geographic Information System (GIS) technology has shown great potential in evaluating the accessibility of fire hydrants and buildings [15], but its dynamic relationship assessment still faces challenges. Internationally, scholars are also actively exploring more advanced fire risk assessment and simulation technologies. For example, Choi et al. [16] used artificial neural networks to explore fire risk assessment models and predict fire accidents in manufacturing facilities.

Overall, existing scholars' research on fire risk and hazard indicators focuses on traditional building fire hazards, such as structural design defects, water, electricity, and gas installations. At the level of numerical simulation, more attention is paid to a single aspect, such as the structural space or decoration design of traditional buildings. Other environmental conditions are analyzed and numerically simulated based on the default values of simulation software for fire safety theory, and the impact of multiple comprehensive influencing factors on teaching buildings is rarely explored. However, these studies often overlook the significant impact of objective factors in nature on the risk of building fires. In fact, natural phenomena such as extreme weather events (such as high temperatures, droughts), strong winds, lightning, etc., may not only directly trigger fires, but also exacerbate the spread of fire, posing serious challenges to the fire prevention performance and personnel evacuation of buildings. These objective factors play a crucial role in the occurrence and development of fires. Therefore, in-depth research on the impact of objective factors in nature on the risk of building fires is of great significance for improving the fire risk assessment system and enhancing fire prevention and control capabilities.

The i-WRBS was introduced by Korean scholars Jeong and Jeong [17] to identify the hazardous hierarchy of fatal accidents in the construction industry. It has been applied in risk identification and assessment in multiple fields such as railway construction safety risks [18], tunnel risks [19], and prefabricated building supply chain risks [20]. In contrast to most existing studies that utilize the WBS and RBS to analyze various risks, the i-WRBS method focuses on identifying hierarchical structures through multiple levels of representation. The first level represents the overall project, the second level consists of sub standards derived from the first, and the third level is composed of further sub standards from the second. This hierarchical structure allows for a recursive approach, facilitating a more detailed identification of risks at each level. The factors influencing the occurrence of fire accidents are complex, diverse, and inherently unpredictable; however, certain correlations exist between some of these factors, which can help in understanding and mitigating fire risks. The DEMATEL method [21] refers to the decision-making experiment and evaluation laboratory technology. As a comprehensive method that combines graph theory and matrix theory, it can identify the mutual influence relationship between complex system elements. Therefore, this article identifies the potential fire risks of teaching buildings in multiple dimensions through literature review and i-WRBS method. The DEMATEL method can reflect the connections between factors, so the EMATEL method is used for evaluation. Based on the above results, variables are selected and simulation analysis is carried out using simulation technology to clarify the degree of fire danger and key area conditions. The rules are summarized to provide guidance for dealing with teaching building fires. The flowchart of this study is shown in Figure 1.

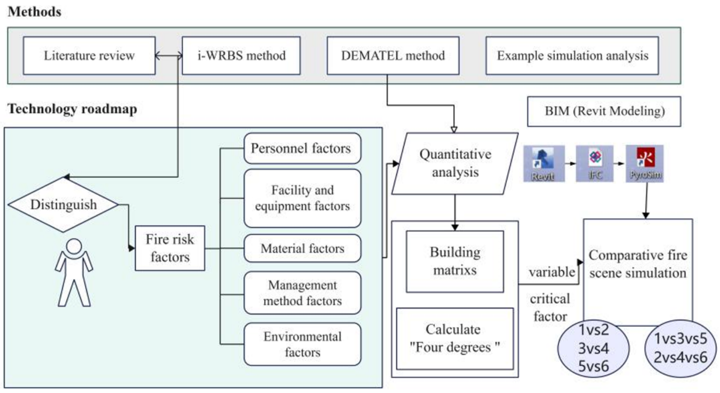


Figure 1. Research process

2 Methodology

2.1 i-WRBS Method Theory

The i-WRBS method theory proposed by Jeong Jaemin and Jeong Jaewook flexibly utilizes the advantages of WBS and RBS to deepen the hierarchical structure through progressive sub standards in the WBS. The first level serves as the final project, and the identification work at this level is a preliminary assessment and macro grasp of the potential risks of the entire project, providing a foundation for further in-depth analysis at subsequent levels. The second level consists of sub standards from the first level, which analyze the components of the project, identify areas where project risks arise, and clarify priorities to ensure comprehensiveness. The third level consists of sub criteria from the second level, which analyze potential research subjects in different fields. Based on this deduction, by refining work units, we can identify the specific impact of different types of work fields and tasks on risks, which helps us better understand and grasp the distribution characteristics of risks in different types of work and tasks, and provides scientific basis for formulating effective prevention and control measures. Further identify specific risk-influencing factors based on the hierarchical structure obtained from WBS. This method can be very useful for analyzing complex and variable potential risk factors such as fire incidents.

2.2 DEMATEL Method

This article uses the DEMATEL method to analyze complex systems, study the internal connections between different factors in complex systems, and determine the importance of each influencing factor. This method accounts for both direct and indirect relationships between factors, allowing for the identification of the key causes of accidents [22]. Specifically, a matrix is constructed to calculate the degree of influence (f_i), the degree of influence (e_i), the centrality (m_i), and the degree of cause (n_i). Based on the data results, the risk factors affecting the occurrence of fire accidents in teaching buildings are analyzed. The specific steps are as follows:

(1) Set influencing factors, represented by the serial number R_i;

(2) Construct an n-order direct impact matrix $X = (X_{\mathrm{ij}})_{\mathrm{n}\times\mathrm{n}}$, experts score according to the scoring principle and take the mode, with scores ranging from 0 to 3 points, indicating the degree of influence of factor Si on factor Sj as no impact, weak, moderate, and strong;

(3) The normalization direct impact matrix $G = (g_{ij})\, n \times n$ is calculated as follows:

$$G = \frac{1}{\max_{1\leq i\leq n} \sum_{j}^{n} X(i,j)} X \tag{1}$$

(4) Construct a comprehensive impact matrix $T = (t_{ij})\, n \times n$, where I refers to the identity matrix, calculated as follows:

$$T = G(I-G)^{-1} \tag{2}$$

(5) Calculate the "four degrees": impact degree (f_i), affected degree (e_i), centrality (m_i), and causality degree (n_i).

$$f_i = \sum_{\mathrm{j=1}}^{\mathrm{n}} \mathrm{t_{ij}} (\mathrm{i} = 1, \ldots, \mathrm{n}) \tag{3}$$

$$e_i = \sum_{\mathrm{j=1}}^{\mathrm{n}} \mathrm{t_{ji}}(\mathrm{i} = 1, \cdots, \mathrm{n}) \tag{4}$$

$$m_i = f_i + e_i(\mathrm{i} = 1, \ldots, \mathrm{n}) \tag{5}$$

$$n_i = f_i - e_i(\mathrm{i} = 1, \ldots, \mathrm{n}) \tag{6}$$

Influence degree refers to the degree to which one factor affects other factors; the degree of influence refers to the degree to which a factor is influenced by other factors; centrality and causality are important indicators for identifying key risk factors. It is the sum of the two, representing the proportion of the factor in all risk factors; It is the difference between this factor and other factors, with positive and negative values. Positive values indicate that this factor has a high impact on other factors, and the effect of such factors is usually described as ”origin type”. Negative values indicate that this factor is less affected by other factors, and this type of factor is usually called ”outcome type”, which means that this type of factor is usually direct or indirect.

2.3 BIM and Pyrosim Software

2.3.1 BIM technology

To ensure accuracy, BIM software Revit is used for the virtual restoration of teaching buildings, which has advantages such as being three-dimensional, refined, and efficient.

2.3.2 Pyrosim simulation

Fire simulation software Pyrosim, as a professional software for researching fires internationally, has the advantages of high visualization, dataization, and scene restoration. Based on BIM models, the software can directly import IFC 3D models and set calculation areas. Traditionally, grid size is inversely proportional to computational accuracy, but the more grids there are, the longer the computational complexity and time span. Based on literature review and FDS fire simulation user manuals, it is known that the criterion for determining grid refinement is often based on the ratio of the characteristic diameter of the fire source to the grid size, which should be between 4-16. The grid determination formula is as follows:

$$\mathrm{D}^* = \left(\frac{\mathrm{Q}}{P_\infty C_P T_\infty \mathrm{g}^{\frac{1}{2}}} \right)^{\frac{2}{5}} \tag{7}$$

where, D^* is the characteristic diameter of the fire source, m; Q is the heat release rate of the fire source, kW; and ρ_∞ is the ambient air density, $\mathrm{kg/m}$; for the specific heat of ambient air, $\mathrm{kJ/(kg \cdot K)}$; T is the ambient air temperature, K; g is the gravitational acceleration, $\mathrm{m/s}$.

3 Empirical Analysis

3.1 Extracting Fire Risk Factors Based on i-WRBS Method

Fire risk identification in teaching buildings is a complex process with multiple levels and dimensions, which requires us to maintain a high level of vigilance and meticulous analysis throughout the entire building activity cycle, from planning, design to construction and acceptance., By comprehensively considering the potential factors of fire in functional areas, fire design, and actual causes of fire accidents, and paying special attention to the existence of natural force majeure factors, we strive to comprehensively and accurately extract the key factors of fire risk in teaching buildings, including traditional risk factors (such as building structure, electrical equipment, personnel behavior, etc.) and natural force majeure factors (such as temperature, strong winds, drought, etc.).

Just capitalize the first letter of words, phrases, and sentences included in tables and figures. Reference each table and figure within the text as Table 1 or Figure 1. Ensure that the caption/title is on the same page with the figure/table.

3.1.1 Preliminary extraction of multi angle fire risk factors

Based on the i-WRBS method theory, the first level is determined as a building project layer by layer, and a preliminary assessment of potential fire risk factors in the teaching building is completed; the second level, as a sub standard of the first level, is defined as architectural design and functional layout. It is a key link in the implementation process of construction projects, directly determining the spatial configuration, form selection, and functional planning of buildings. In this process, it is not only necessary to consider the effectiveness and aesthetics of the building, but also to pay attention to its safety, especially the control of fire risks. Through in-depth analysis of architectural design and functional layout, fire risks can be identified and reduced from the source, ensuring that buildings have high safety during the design and planning stages. The third level, as a sub standard of the second level, is defined as facility system engineering. It is the process of designing, installing, and debugging various facilities of a building (such as electrical, plumbing, fire protection, ventilation, etc.) based on building design and functional layout. The design and installation quality of these facility systems are directly related to the normal operation and safety of building functions. Especially in the event of a fire, the effectiveness and reliability of the fire protection system are crucial for personnel evacuation and fire suppression. Therefore, in-depth analysis of facility system engineering is a key step in further refining fire risk identification, which helps us ensure the safety and reliability of various facility systems. In the fourth level hierarchical structure, it is further refined into job types and task divisions. The implementation of facility system engineering requires specialized division of labor and skill requirements, and different types of work and tasks have varying degrees of impact on fire risk. Finally, in the fifth level hierarchy, based on the analysis of the first four levels, specific fire-influencing factors are further identified.

3.1.2 Constructing a risk hierarchy structure using i-WRBS method

As the first level of the WBS, the teaching building's architectural design and functional layout are the second level. According to literature review, potential risks exist in five parts: functional zoning, building engineering [23, 24], fire engineering [25, 26], and decoration engineering; the third level is refined into electrical systems, ventilation and air conditioning systems, and water supply and drainage systems; the work task content corresponding to the fourth level is determined by system engineering. Based on this summary, the fifth level risk decomposition structure is obtained, and potential factors of fire risk are identified, as shown in Figure 2 below.

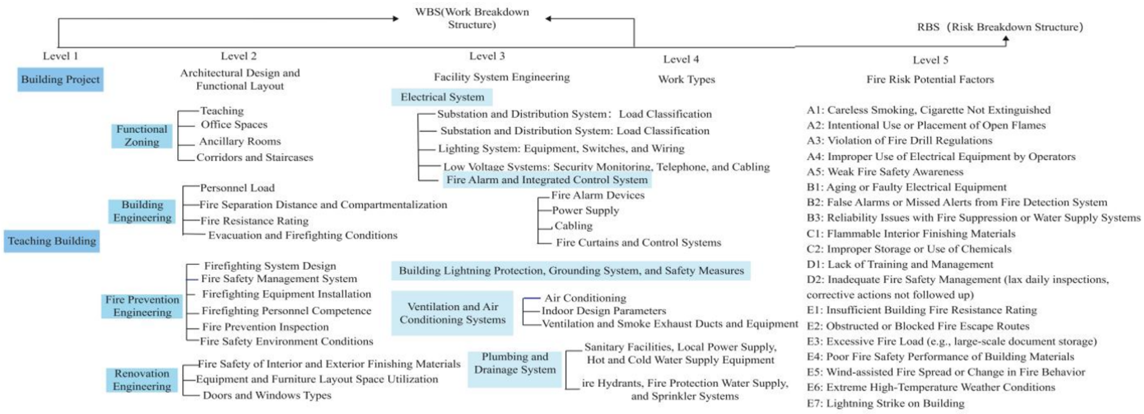


Figure 2. Diagram of the i-WRBS hierarchical decomposition structure

These factors cover all aspects from building design and functional layout to facility systems engineering to job types and task division. Through the i-WRBS five-level structure, 19 potential fire influence factors are preliminarily extracted, divided into five categories, personnel factors (A), facilities and equipment factors (B), material factors (C), management methods factors (D), environmental factors (E), it is embodied in careless smoking, non-extinguished cigarette ends (A_1), aging/failure of electrical equipment (B_1), flammable decoration materials (C_1), lack of training management (D_1), and insufficient fire resistance grade of buildings (E_1). These factors are the concrete manifestation of the fire risk of teaching buildings, and also the focus of the follow-up fire risk prevention and control work.

To ensure the rationality and scientific validity of each index within the potential fire risk factor system, a membership degree analysis was conducted using a questionnaire survey method. The questionnaire was distributed in the online form to experts with many years of experience, the Likert Scale 5 was used to judge the importance of the extracted indicators, and the scores from 1 to 5 indicated" Not important" to" Very important". The average value of the data is calculated, and then the membership degree is judged by the formula RN = Xn/LN, where XN denotes the number of people whose expert scores are higher than the average value, LN denotes the total number, and RN denotes the membership degree of the Index. Set the critical value of 0.6, if the membership degree of an index is greater than 0.6, it is retained; otherwise, it is eliminated.

A total of 98 questionnaires were distributed, and 84 valid responses were received, resulting in an effective response rate of 85.7%. The analysis of the questionnaire results showed that the average value of each index reached 3, indicating that the preliminary indicators align with objectivity. Further data analysis revealed that a smaller variance corresponds to a more accurate critical value. An index was retained if its membership degree exceeded 0.6; otherwise, it was excluded. Only the top three choices from the survey were selected and tallied based on the frequency of selection.

The questionnaire is shown in Figure 3 below. The three-dimensional coordinates indicate the type of experts, the number of respondents, and the percentage of participants. The participants are mainly from colleges and universities (20.41%) and fire departments (18.37%). In terms of years of experience, 33.67% of the experts had 3 years of experience or more to less than 6 years, and in terms of professional titles, zero per cent of the experts had junior professional titles or no professional titles (40.82%). The membership levels are summarized in Table 1 below, which gives the final retained risk indicators greater confidence in the fire risk assessment of the project.

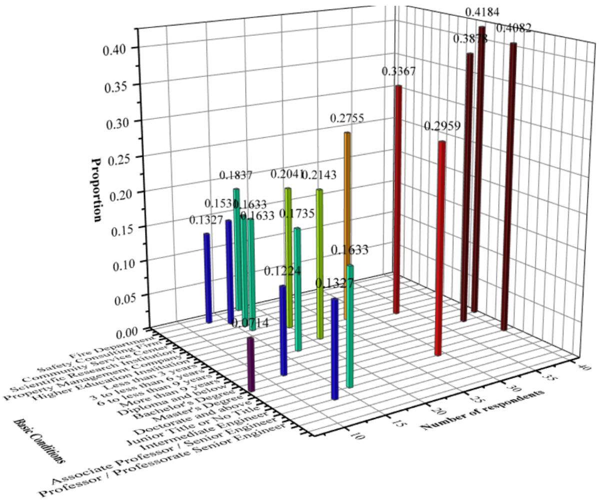


Figure 3. Diagram of the i-WRBS hierarchical decomposition structure

Based on the results, 15 indicators were ultimately determined, and 3 indicators were removed from the membership degree, namely A_3, B_2, E_7. The reasons are: violation of fire drill regulations, false alarms or omissions in the automatic fire alarm system, insufficient fire resistance rating of buildings, and poor fire performance of buildings. They mainly involved in systemic or structural problems, rather than directly attributed to personnel, facilities, equipment, materials, management methods, or environmental factors. These factors are not directly related to individual behavior, operating methods, or external environmental conditions in determining potential fire risks, but rather focus more on the standardization of building design, facility configuration, and equipment functionality. At the same time, experts have proposed that E_1 and E_4 overlap. After comprehensive consideration, E_1 is defined as an insufficient fire resistance rating and poor fire performance. The summary of fire hazards is shown in Figure 4:

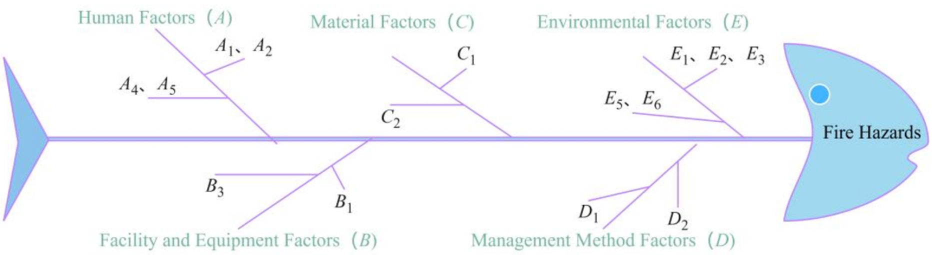


Figure 4. Fire hazard fish bone diagram

3.2 Fire Factor Evaluation Based on DEMATEL Method

3.2.1 Indicator determination and risk influencing factor analysis

Based on data results, the risk factors that affect the occurrence of fire accidents in teaching buildings were analyzed. Fire risk factors were set, represented by R1-R15, and are shown in Table 2 below.

Based on the 15 fire risk factors listed in Table 2, a focus group was organized to evaluate the relationships between each influencing factor. The group comprised 12 members, with three experts selected from each of four categories: building fire design professionals, fire station managers, researchers specializing in university teaching buildings, and personnel with extensive knowledge of teaching buildings. All members possessed considerable practical and research experience. The mode of scores was taken to determine the degree of influence of each factor on other factors. Based on this, a direct impact matrix (see diagram in Figure 5) and a comprehensive impact matrix (see diagram in Figure 6) were constructed. Matlab was used for data analysis, and the results are shown in Table 3 and Figure 7 below.

Table 1. Summary of membership degree

First Level Indicators	Second Level Indicators	Membership Degree	Whether to Retain
Personnel factors (A)	A_1: Careless smoking and non-extinguishing cigarette butts	0.71	√
	A_2: Intentionally using or releasing open flames	0.60	√
	A_3: Violation of fire drill regulations	0.51	×
	A_4: Improper use of electrical appliances by equipment operators	0.65	√
	A_5: Weak awareness of fire safety	0.63	√
Facility and equipment factors (B)	B_1: Aging/malfunction of electrical equipment	0.66	√
	B_2: False or missed alarms in the automatic fire alarm system	0.56	×
	B_3: Reliability issues with fire water supply or fire extinguishing	0.63	√
Material factors (C)	C_1: Decoration materials are flammable	0.60	√
	C_2: Improper storage or use of chemicals	0.63	√
Management method factors (D)	D_1: Lack of training management	0.63	√
	D_2: Improper fire management (lack of strict daily inspections and inadequate rectification)	0.69	√
Environmental factors (E)	E_1: Insufficient fire resistance rating and poor fire performance	0.72	√
	E_2: The fire escape is not smooth	0.63	√
	E_3: Excessive fire load	0.64	√
	E_4: Poor fire resistance performance of buildings	0.60	√
	E_5: Wind assisted fire or alteration of fire intensity	0.61	√
	E_6: Extreme high temperature weather	0.62	√
	E_7: Lightning strikes buildings	0.52	×

X	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	R_{11}	R_{12}	R_{13}	R_{14}	R_{15}
R_1	0	1	0	0	1	0	1	1	0	0	1	0	1	1	0
R_2	1	0	1	2	1	1	2	2	2	3	2	1	1	3	1
R_3	0	1	0	1	2	1	1	1	1	1	2	1	2	1	0
R_4	1	2	2	0	2	1	2	1	3	3	2	3	2	2	2
R_5	1	1	3	2	0	2	1	2	1	2	2	1	2	2	0
R_6	0	1	1	1	2	0	1	2	1	2	2	1	2	2	1
R_7	1	2	1	2	1	1	0	2	2	2	1	2	3	2	2
R_8	1	2	1	2	2	1	2	0	3	2	1	3	2	3	1
R_9	1	2	2	3	2	1	1	1	0	3	2	2	2	1	0
R_{10}	2	3	2	3	3	2	2	3	3	0	3	3	2	2	2
R_{11}	1	2	2	2	2	1	1	2	2	3	0	2	2	3	1
R_{12}	1	1	2	3	2	1	2	2	3	2	2	0	3	2	1
R_{13}	1	1	2	2	2	2	3	2	3	2	3	3	0	3	2
R_{14}	1	3	1	2	2	1	2	3	2	2	3	2	3	0	3
R_{15}	0	1	0	2	1	1	2	1	1	2	2	1	2	3	0

Figure 5. Fire risk factor n-order direct impact matrix

Table 2. Fire risk factors

Serial Number	Fire Risk Factors	Number
R_1	Careless smoking and non-extinguishing cigarette butts	A_1
R_2	Intentionally using or releasing open flames	A_2
R_3	Improper use of electrical appliances by equipment operators	A_4
R_4	Weak awareness of fire safety	A_5
R_5	Aging/malfunction of electrical equipment	B_1
R_6	Reliability issues with fire water supply or fire extinguishing systems	B_3
R_7	Decoration materials are flammable	C_1
R_8	Improper storage or use of chemicals	C_2
R_9	Lack of training management	D_1
R_{10}	Improper fire management (lack of strict daily inspections and inadequate rectification)	D_2
R_{11}	Insufficient fire resistance rating and poor fire performance	E_1
R_{12}	The fire escape is not smooth	E_2
R_{13}	Excessive fire load	E_3
R_{14}	Wind assisted fire or alteration of fire intensity	E_5
R_{15}	Extreme high temperature weather	E_6

X	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	R_{11}	R_{12}	R_{13}	R_{14}	R_{15}
R_1	0.02	0.06	0.03	0.04	0.06	0.02	0.06	0.06	0.04	0.04	0.07	0.04	0.07	0.07	0.02
R_2	0.09	0.11	0.12	0.18	0.14	0.10	0.16	0.17	0.18	0.22	0.18	0.15	0.16	0.21	0.11
R_3	0.04	0.10	0.07	0.11	0.13	0.08	0.10	0.11	0.11	0.12	0.14	0.11	0.14	0.12	0.05
R_4	0.10	0.18	0.17	0.15	0.19	0.12	0.18	0.17	0.23	0.24	0.21	0.22	0.21	0.21	0.14
R_5	0.08	0.13	0.17	0.17	0.11	0.13	0.13	0.16	0.15	0.18	0.17	0.14	0.18	0.18	0.07
R_6	0.05	0.12	0.11	0.13	0.15	0.06	0.11	0.15	0.13	0.16	0.16	0.13	0.16	0.16	0.06
R_7	0.09	0.17	0.13	0.19	0.15	0.11	0.11	0.17	0.19	0.19	0.16	0.18	0.22	0.19	0.13
R_8	0.09	0.18	0.14	0.20	0.18	0.11	0.17	0.13	0.23	0.20	0.17	0.22	0.20	0.23	0.11
R_9	0.09	0.16	0.15	0.21	0.17	0.10	0.13	0.14	0.13	0.21	0.18	0.17	0.18	0.16	0.07
R_{10}	0.14	0.23	0.19	0.26	0.24	0.16	0.20	0.24	0.26	0.19	0.26	0.25	0.24	0.25	0.16
R_{11}	0.09	0.18	0.16	0.20	0.18	0.11	0.15	0.18	0.20	0.23	0.15	0.19	0.20	0.23	0.11
R_{12}	0.10	0.15	0.17	0.23	0.19	0.12	0.18	0.19	0.23	0.21	0.20	0.14	0.23	0.21	0.11
R_{13}	0.10	0.17	0.18	0.22	0.20	0.15	0.22	0.20	0.25	0.23	0.25	0.24	0.17	0.25	0.15
R_{14}	0.10	0.22	0.15	0.22	0.20	0.12	0.19	0.23	0.22	0.23	0.24	0.21	0.25	0.18	0.18
R_{15}	0.05	0.12	0.09	0.17	0.13	0.09	0.15	0.13	0.14	0.17	0.17	0.14	0.17	0.20	0.07

Figure 6. Comprehensive impact matrix of fire risk factors

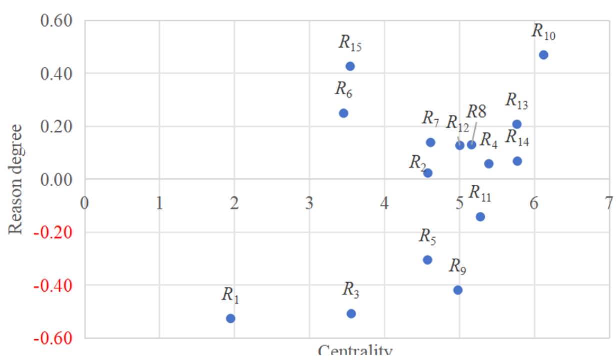


Figure 7. Analysis of cause degree and centrality of factors influencing fire risk

Table 3. Comprehensive impact relationship of fire risk factors in teaching buildings

Risk Factor Number	Influence Degree (f_i)	Affected Degree (e_j)	Centrality (m_i)	Reason Degree (n_j)
R_1	0.71	1.24	1.95	-0.53
R_2	2.30	2.28	4.58	0.02
R_3	1.52	2.03	3.56	-0.51
R_4	2.73	2.67	5.39	0.06
R_5	2.13	2.44	4.57	-0.30
R_6	1.85	1.60	3.45	0.25
R_7	2.38	2.24	4.61	0.14
R_8	2.57	2.44	5.01	0.13
R_9	2.28	2.70	4.98	-0.42
R_{10}	3.30	2.83	6.12	0.47
R_{11}	2.57	2.71	5.28	-0.14
R_{12}	2.65	2.52	5.16	0.13
R_{13}	2.99	2.78	5.77	0.21
R_{14}	2.92	2.85	5.77	0.07
R_{15}	1.98	1.56	3.54	0.43

3.2.2 Result analysis

The results showed that the risk factors with high impact (f_i) include R_{10} (improper fire management), with an impact of 3.30 , significantly higher than other factors. This indicates that inadequate fire management has a significant impact on the overall fire safety system, especially when daily inspections and rectification are not in place. R_2 (intentional use or release of open flames) and R_{13} (excessive fire load) are 2.30 and 2.99 , respectively. These factors indicate that improper use of open flames or excessive fire load before a fire occurs can easily lead to large-scale fires. These factors indicate that management negligence (such as improper fire management) and human behavior (such as intentionally releasing open flames) are the most important aspects of fire risk management, with significant impact and the ability to trigger a series of safety accidents. R_{14} (wind assisted fire or altered fire), with an impact degree of 2.92 , indicates that wind has a significant impact on the occurrence and development of fires, especially in accelerating the spread of fires and making them more uncontrollable. Especially in multi-story building fires, the role of wind is particularly significant. The factors with a high degree of influence e_i include: R_9 (lack of training management), with an influence degree of 2.70 , indicating a lack of systematic training and management measures, which leads to insufficient ability of employees to cope with fire risks, thereby affecting overall safety. R_{12} (fire escape obstruction), with an impact degree of 2.52 , indicates that the smoothness of the fire escape is influenced by multiple factors, including equipment, management, and personnel cooperation. These factors belong to the category of "outcome-based" factors, which usually arise when management measures are inadequate or the environment does not comply with safety regulations, and are influenced by other factors. Therefore, for such factors, it is necessary to pay attention to process management and technical support, and promptly identify and fix possible problems.

Centrality (m_i) and causality (n_i) are important indicators for evaluating the relationship between influencing factors. The results show that R_{10} (improper fire management) and R_{13} (excessive fire load) have high centrality, 6.12 and 5.77, respectively, while their causality is 0.47 and 0.21, respectively. This indicates that these two factors are not only at the core of the fire risk management network, but also play a decisive role in the overall fire risk composition of the system. R_2 (intentional use or release of open flames) has a centrality of 4.58 and a causality of 0.02, indicating that although it has a high centrality in the fire risk network, its root cause is not complex, mainly due to human misconduct. R_4 (weak awareness of fire safety) and R_7 (flammable decoration materials) have centrality values of 5.39 and 4.61, respectively, but their causality values are 0.06 and 0.14, indicating that although these factors occupy a relatively central position in the network, the fundamental reasons behind them are mainly related to fire education and material selection standards, which are safety hazards caused by environmental and management deficiencies.

Overall, improper fire management (R_{10}) and excessive fire load (R_{13}) are core factors in fire risk management, both of which have a significant impact on the overall safety system. Improving fire management and strictly controlling fire load should be the primary measures to prevent fires. Wind-assisted fire or alteration of fire intensity (R_{14}) is also an important factor, especially in complex multi-story building fires where the effect of wind accelerates the spread of fire. Therefore, special attention should be paid to the impact of environmental factors in fire prevention and control.

Lack of training management (R_9) and poor access to fire exits (R_{12}) are "outcome-oriented" factors that are greatly influenced by other factors, mainly manifested as omissions in management and technical processes. Therefore, strengthening training management and ensuring smooth fire exits are key to improving safety. The weak awareness of fire safety (R_4) and the flammability of decoration materials (R_7) are the "origin type" factors, and it is necessary to start from regulations and standards, strengthen personnel's safety awareness education, and ensure that building materials meet fire safety requirements. Overall, improving the fire management system, strengthening training, and implementing fire prevention standards are key measures to reduce fire risks at present.

3.3 Example Fire Simulation

In the DEMATEL analysis results, natural environmental factors are identified as important objective factors. Therefore, this paper simulates the interaction model between wind speed and building structure to reveal the accelerating effect of wind direction and wind speed on fire spread, especially in complex multi-story buildings. Taking the teaching building as the research object, this study investigates the impact of wind as a variable on the occurrence of fires on different floors. Through comparative analysis of smoke spread and temperature changes, it provides a certain reference for accurate response and evacuation of various personnel in different scenarios of fires.

3.3.1 Overview of the target teaching building

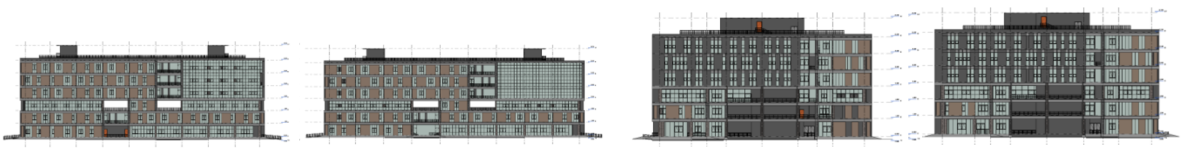
The target teaching building integrates teaching, office, and research functions, covering a total area of $13,774.36$ square meters. It consists of six floors above ground, with a partial seventh floor, and features spacious rest platforms on the third and fifth floors. The first floor is 4.2 meters high, and the second to sixth floors are 3.8 meters high. The height of the protruding staircase in some areas is 4.5 meters, with a total height of 27.7 meters; the fire resistance rating is Level 2. The teaching building is a hollow rectangular structure formed by connecting two L -shaped sections, with a main column grid size of $9.0 \text{ m} * 8.4 \text{ m}$. The building features a frame structure, and the interior includes glass curtain walls as part of the enclosing facade. The interior is equipped with customized fire-resistant aluminum alloy doors and windows, solid wood composite doors, etc. The distribution room and duty room are located on the first floor, and the internal functional zoning of the teaching building is shown in Table 4. Each floor has 2 bathrooms (including accessible bathrooms), and one bathroom contains a storage room. The external walls are insulated with fire-resistant treated extruded polystyrene board. with a fire resistance performance of B_1 level.

Table 4. Division of functional areas of the target teaching building

Floor	40 Person Classroom	80 Person Classroom	Teacher's Lounge	Locker Room	Rest Area	Rest Platform
1	10	0	2	1	0	0
2	14	0	2	1	2	0
3	6	4	2	1	2	2
4	9	6	2	1	2	0
5	9	6	2	1	2	2
6	9	6	2	1	2	0

3.3.2 Application of BIM technolog

(1) Establishment of 3D Model BIM software, specifically Revit, was used for the virtual restoration of the teaching building. The Revit models of the building's local structure and facade are shown in Figure 8.



(a) (b) (c) (d)

Figure 8. The facade of the teaching building: (a) North elevation; (b) South elevation; (c) East elevation view; (d) West elevation view

The teaching building features four staircases and two elevators. Fire doors are installed at the entrances of the staircases, typically remaining open. The east and west entrance halls serve as the primary entry and exit passages, with their layout depicted in Figure 9.

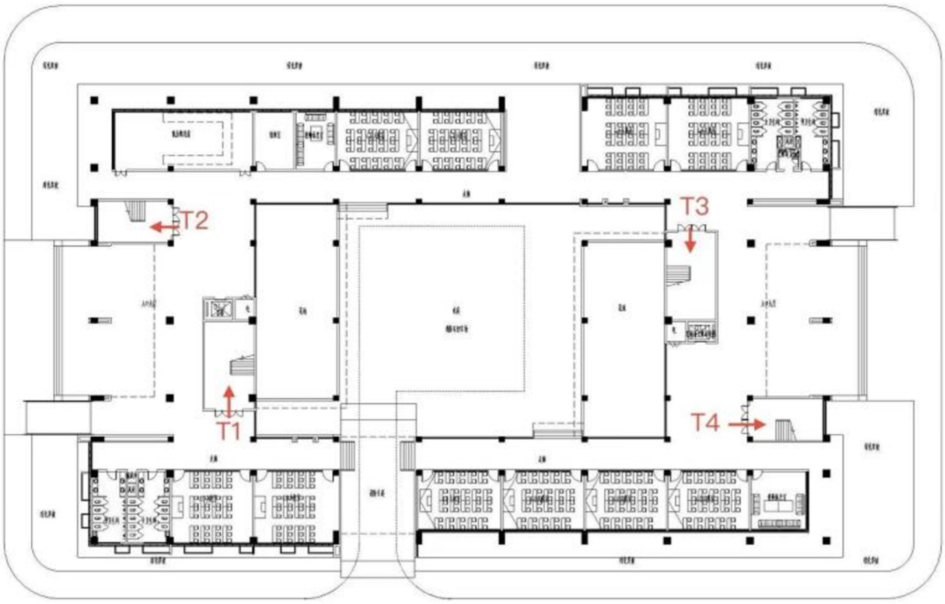


Figure 9. Distribution of building stairs, elevators and corridors

(2) Model import into Pyrosim and initial parameter setting

The 3D model was imported into Pyrosim, and the proposed fire source is a sofa product, with lightweight curtains nearby. Therefore, the combustion type is ultra-fast. The time to reach steady state is determined based on the fire growth type T2 fire. According to the heat release rate calculation formula $Q = \mathrm{at}^2$ (where Q is the heat release rate (KW), a is the fire development coefficient $\left(\mathrm{kW/s^2}\right)$, and t^2 is the fire development time (s), since the heat release rate in offices and classrooms needs to meet $Q = 6MW$ to reach steady state without a sprinkler, it takes 178 s to reach steady state. Based on the grid determination formula, the grid size range is $0.22 - 0.86$.

Taking into account the characteristics of the research object, software operation, and the research experience of existing scholars, it is divided into a dual zone model. Based on the research object of university teaching buildings by existing scholars, the impact of grid refinement on its calculation accuracy is simulated, analyzed, and evaluated. The results show that the two types of grid refinement, medium and fine, do not have a significant impact on the calculation accuracy and are basically unaffected. Therefore, to ensure accurate and efficient simulation, the X-axis is divided into left and right different grids, with X=62 as the boundary point, and the grid size containing the fire source area is set to 0.5m; the grid size in the area away from the fire source is 1.0m, with a total of 349440 grids.

(3) Working condition setting

The research object of this paper is a public teaching building in a university. Each functional area is a natural smoke exhaust system, and there is no mechanical smoke exhaust. The fire point is the East Teachers' lounge on different floors; a light sofa with $0.75 * 2.0 = 1.5\ \mathrm{m}^2$ is proposed as the fire source, so the heat release rate per unit area is 4000 kW in steady state; the indoor and outdoor temperature detectors of each floor are 2 m away from the floor elevation; the partition equipment of each floor is located at the stairway, the height is the height of the floor. The 2 d temperature slices of each floor are 2 m from the floor elevation in the transverse slice and $\mathrm{x} = 80\ \mathrm{m}$ in the longitudinal slice.

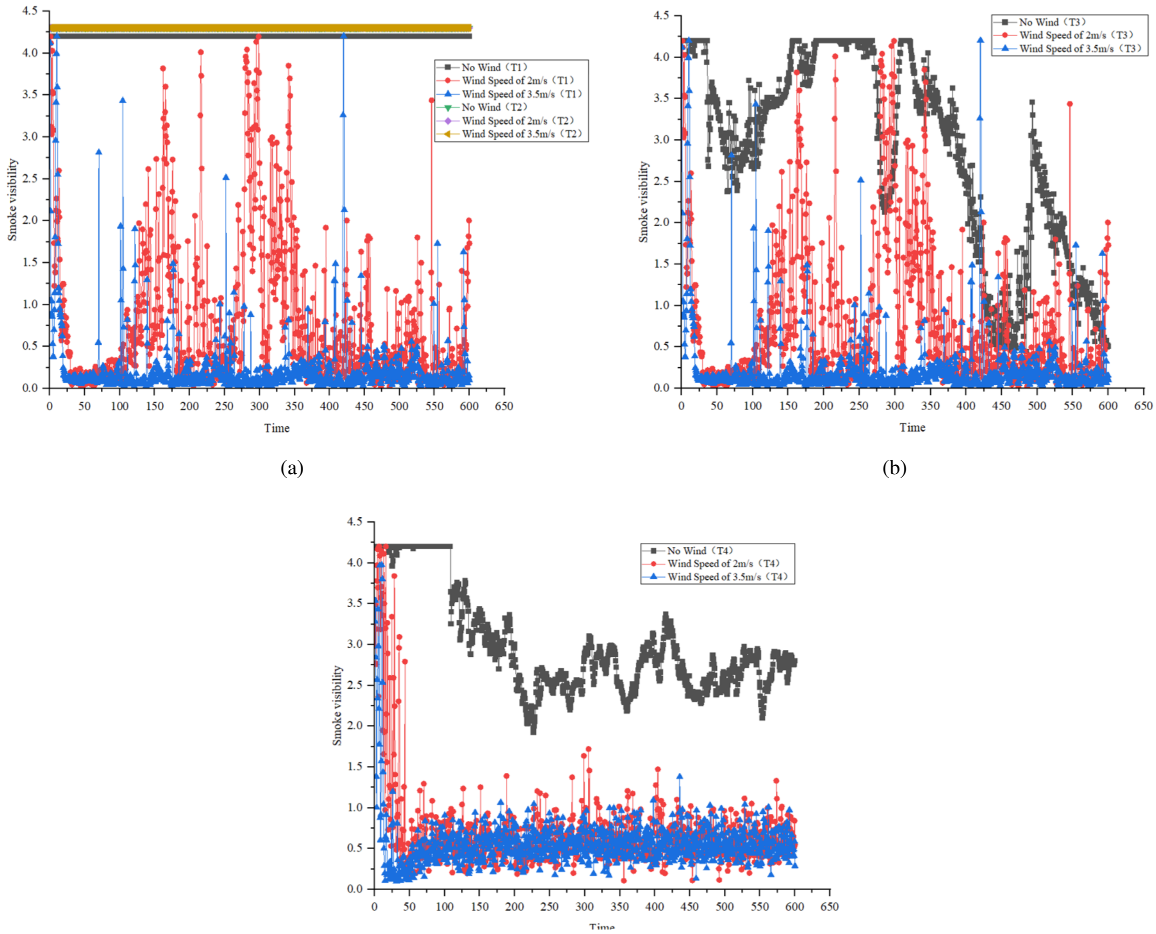
It is proposed to install six temperature detectors on each floor, which are located at the door of the room, above the fire source, and at the evacuation exits of the four stairs, which correspond to the T1-T4 stairs. The temperature detectors are represented as I-D00, i-D0, I-D1 through I-D4, and I indicates the floor. The first floor is crowded, with high fire risk and difficult evacuation. The third floor serves as the middle level, characterized by frequent personnel movement and complex evacuation routes, making it particularly susceptible to fire and smoke spread. Based on observations and data comparisons of seasonal wind direction and speed from a specific area in Jiangxi Province, using China's meteorological data, the external environment of the model is influenced by a southeast wind, with a direction of 120 degrees according to meteorological standards. The wind speed is recorded at 2 m/s (light wind) and 3.5 m/s (light wind). Therefore, the specific working condition of the fire simulation is designed as scene 135 is the first floor, and the fire occurs in the East Teachers' lounge under three conditions of no wind, 2 m/s and 3.5 m/s wind speed, and scene 246 corresponds to the third floor.

3.4 Fire Simulation Results

The results show that the temperature curves of 1-D1 and 1-D2 are almost unchanged throughout the whole process, indicating that due to the distance between the first and second stairwells and the fire source, with the diffusion of smoke and heat, the temperature of the first and second stairwells is far away from the fire source, it is almost not affected by the temperature, so the temperature measurement of T1 and T2 stairs is omitted in the subsequent 600 s simulation, thus improving the efficiency of numerical simulation.

3.4.1 Effect of wind speed on smoke dispersion

(1) Analysis of smoke diffusion in the same floor under different wind speeds The simulation results show the smoke visibility of each stairway under different working conditions of the first floor, as shown in Figure 10 below.



(a) (b)

(c)

Figure 10. (a) Smoke visibility of T1 and T2 at ground level; (b) First layer T3 smoke visibility; (c) First floor T4 smoke visibility

From the subgraph (a) of Figure 10, it can be seen that only the red and blue curves fluctuate greatly from 0 to 600 s under the three conditions of no wind, 2 m/s and 3.5 m/s wind speed. When the wind speed is low, the smoke visibility fluctuates greatly and disperses. With the increase of wind speed, the visibility is concentrated in the lower position (about 0.25 m), during the whole fire process, whether there is wind or not, it will not have an impact on the T2 staircase, indicating that in case of fire, evacuation should first be carried out at a distance from the fire source, and in order to prevent too many people, more evacuation exits can be made.

It can be seen from the subgraph (b) of Figure 10 that under the condition of no wind, the smoke entering the T3 staircase first fills the upper floor of the staircase, and the smoke spreads downwards about 30s, and the visible height is 2.4 m at 75s; at the same time, the smoke also spreads to the second-floor stairs. As the smoke continues to enter and spread upward, there will be four decreases in visibility within 600s, and the visibility is nearly 2 m in 300 s, and the next half-floor stairs are covered by smoke; in 440 s, the visible height of the first floor decreased to 0.4 m, and the duration was nearly one minute, which showed that the evacuation of the second floor should be completed within 7 minutes in the windless state. Under the wind speed of 2 m/s, the smoke will quickly reach the T3 staircase entrance, and its visibility will reach 0.2 m in about 25s, and then there will be fluctuations, and the visibility height of the smoke in the first 600s is concentrated in 0-1 m, as the fire continues; when the smoke diffuses upward, there will be a large fluctuation of smoke. Under the wind speed of 3.5 m/s, the visibility of smoke is concentrated below 0.5 m from 16s, so in general, whether there is wind has a great influence on the visibility of T3 stairs; whether it should be used as an evacuation port should be carefully selected according to the actual situation. If other evacuation ports are closed, there is a certain evacuation time when there is no wind or the wind speed is very small, but due to the rapid change of visible height, personnel protection needs to be done.

From the subgraph (c) of Figure 10, it can be concluded that in the absence of wind, the visibility height of T4 gradually decreases at around 100S, and then fluctuates at a visibility height of 2m or more. In the absence of wind and extremely urgent situations, protective measures should be taken for short-term evacuation. When there is wind, the visibility of smoke will rapidly decrease to around 0.2-1m, which cannot meet the evacuation requirements and should not be used as an evacuation exit.

The simulation results show the smoke visibility at each staircase entrance under different working conditions on the third floor, as shown in Figure 11.

By observing the smoke visibility curves at the entrances of stairs T1 and T2, it can be concluded that if a fire occurs at the same coordinate space on the third floor, as the wind speed increases, the stairs T1 and T2 facing the opposite direction will not be affected.

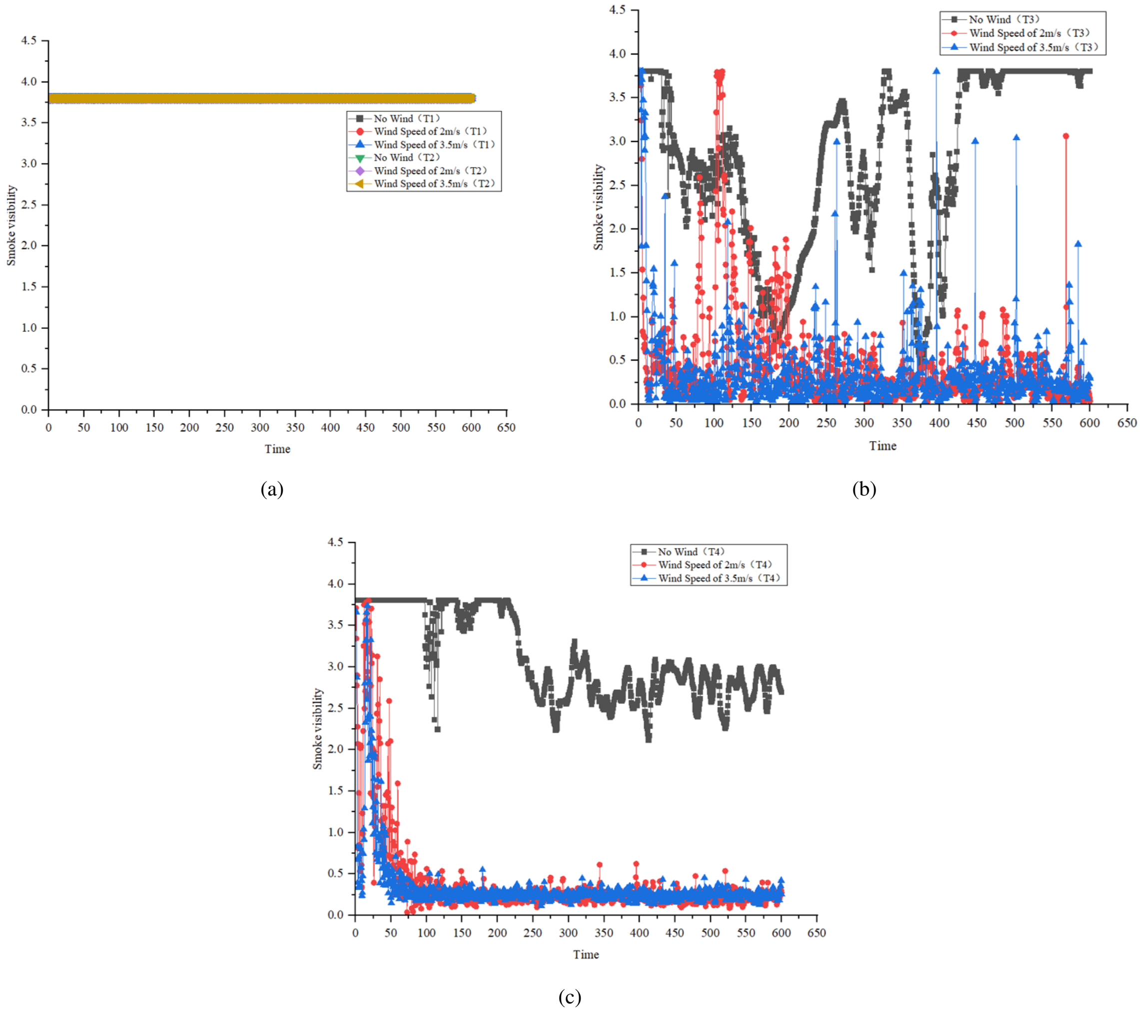


Figure 11. (a) Smoke visibility of T1 and T2 on the third floor; (b) T3 smoke visibility at different wind speeds on the third floor; (c) T4 smoke visibility at different wind speeds on the third floor

For staircase T3, as shown in the subgraph (b) of Figure 11, the visible height of smoke begins to decrease after about 36 seconds in a windless state, fluctuating within a range of 2-2.5 meters within 2 minutes. Then, the smoke height drops to 0.75 meters within 50 seconds. At 175 seconds, smoke diffusion accelerates and visibility improves, causing significant fluctuations during the continuous combustion of the fire. The lowest visibility is 0.5 meters in the last 375 seconds, and then the smoke visibility continues to increase, meeting the requirements for crowd passage. Therefore, the time available for emergency evacuation from the smoke layer surface is 2 minutes. Subsequently, under the influence of the fire, evacuation needs to comprehensively consider the toxic gases in the smoke and their height changes; In windy conditions, smoke will reach T3 exit within about 10 seconds of the fire, and the visibility of smoke will quickly drop below 0.5m, fluctuating around 0-0.5m. Therefore, if there is already an open flame at the fire source and there is natural wind outside, T3 should not be used as the preferred evacuation exit.

From the subgraph (c) of Figure 11, it can be seen that there is a similar development trend of smoke visibility height at the T4 and T3 stairwells when there is wind, both of which will decrease to below 0.5m in a short period of time. However, when there is no wind, the smoke starts to change around 100s, and then fluctuates less within 2 minutes because it mainly covers the floor slab. It starts to fluctuate between 2.1m and 3.5m around 225s. This is because the window opening at the stairwell overlaps with the wind direction at some angles, and the smoke flow is affected by the air circulation through the window, reducing the speed of smoke diffusion downwards. Therefore, the change in smoke height at T4 can provide a period of evacuation time, which is different from the commonly believed idea that the staircase closest to the fire should not be used as an evacuation exit. It is feasible for the crowd on each floor to evacuate downwards through the T4 staircase and leave through the lobby within a considerable amount of time.

(2) Analysis of smoke diffusion on different floors under the same wind speed

Based on the analysis of smoke diffusion at the staircase entrances of the first and third floors under different wind speeds in the subgraph (a) of Figure 9 and the subgraph (a) of Figure 10, it can be concluded that the smoke visibility at the T1 and T2 staircase entrances of the first and third floors remains at the floor height in the absence of wind. It can be inferred that the occurrence of a fire in the southeast corner will not affect the smoke changes in the southwest and northwest directions of the staircase when there is no wind. As the wind speed increases, T2 will never be affected, and smoke will not enter it. It is quite safe in the event of a fire. However, it is worth noting that at wind speeds of 2m/s and 3.5m/s on the first floor, smoke will enter the staircase entrance of T1 and quickly drop to a non safe height. Therefore, when considering the external natural wind, the size and height of the wind have a significant impact on the selection of the staircase evacuation exit. The higher the wind speed, the more severe the smoke will be in the downwind direction of the staircase entrance on lower floors, so it is not suitable as a crowd evacuation passage.

From the above the subgraphs (b) and (c) of Figure 9 and the subgraphs (b) and (c) of Figure 10, it can be seen that the T3 and T4 stairwells will be affected by smoke in any situation, that is, the stairs closer to the fire are more likely to be affected by fire smoke. It can be seen that at a wind speed of 3.5 m/s, the visible height of smoke in the T3 staircase decreases rapidly in both the first and third floors, while at 2 m/s, the visible height of the third floor decreases faster and is concentrated at a lower position (0-0.5 m), while the first floor decreases relatively slowly and fluctuates greatly; In the absence of wind, the visibility of smoke in the first 400s of the first floor is higher than 1.7 m, and in the first 150s of the third floor, it is higher than 1.7 m. It can be seen that the height of the floor will affect the diffusion speed of smoke, which is due to the influence of pressure and air. Higher positions will accelerate the spread of smoke; the development trend of the T4 staircase on the first and third floors under the same wind speed is similar. In the absence of wind, the visibility of smoke on the first floor is concentrated at 2-3 m, on the third floor at 2.5-3.5 m, on the first floor with wind, the visibility height of smoke is concentrated at 0.2-0.7 m, and on the third floor below 0.5 m. Overall, as the floor height increases, the visible height of smoke inside the stairs shows a similar trend. However, under the same working conditions of the same wind direction and speed, the height decreases, and the increase in wind speed will add to the fluctuation of smoke height.

The smoke diffusion on the same floor under varying wind speeds demonstrates that, under windless conditions, smoke diffusion primarily relies on thermal buoyancy. That is, the smoke rises due to heating and subsequently undergoes natural convection within the interior space of the building. In this case, the diffusion speed of smoke is relatively slow and mainly affects the area near the fire source. Under low wind speed conditions, the effect of wind begins to manifest, but it has not yet reached a level sufficient to completely alter the smoke diffusion path. At this point, the spread of smoke is influenced by both thermal buoyancy and wind propulsion. This dual effect may cause smoke to fluctuate and disperse in localized areas such as stairwells. Under high wind speed conditions, the effect of wind becomes very significant, enough to completely change the diffusion path of smoke. At this time, the smoke mainly spreads along the wind direction, and the diffusion speed is greatly accelerated. Due to the high wind speed, smoke can quickly reach areas far away from the fire source, resulting in a rapid decrease in visibility in key evacuation routes such as stairwells.

In actual fires, if there is natural wind or artificial ventilation equipment outside, the influence of wind speed on smoke diffusion should be fully considered, and appropriate evacuation routes should be selected. For higher floors of buildings, smoke may be relatively less affected by wind, but attention should be paid to changes in wind direction and speed in order to take timely response measures.

Analysis of smoke diffusion on different floors under the same wind speed shows that on lower floors, smoke is more susceptible to the influence of wind due to its proximity to the ground wind source. In addition, low-rise building structures and obstacles may also hinder the flow of wind, leading to the accumulation of smoke in localized areas. On high floors, smoke is relatively less affected by wind because it is far from the ground wind source. However, if there are openings or ventilation devices in high-rise buildings, smoke may still spread through these openings.

For low floor areas, special attention should be paid to the direction and speed of wind flow in order to take timely measures, such as closing doors and windows, using wet towels, etc., to reduce smoke intrusion. For high floor areas, although smoke may be less affected by wind, it is still necessary to remain vigilant and be prepared to take emergency measures at any time.

3.4.2 The effect of wind speed on temperature changes

When the smoke temperature reaches 60 degrees Celsius, the human body can tolerate it for a brief period; however, prolonged exposure can be harmful. This article selects a temperature of 60 degrees Celsius at a vertical height of 2 meters from the ground as the judgment standard.

(1) Analysis of temperature curves at measuring points on the same floor under different wind speeds

Export the temperature curves of each measurement point at different wind speeds in the first layer from the Pyrosim simulation results, as shown in Figure 12.

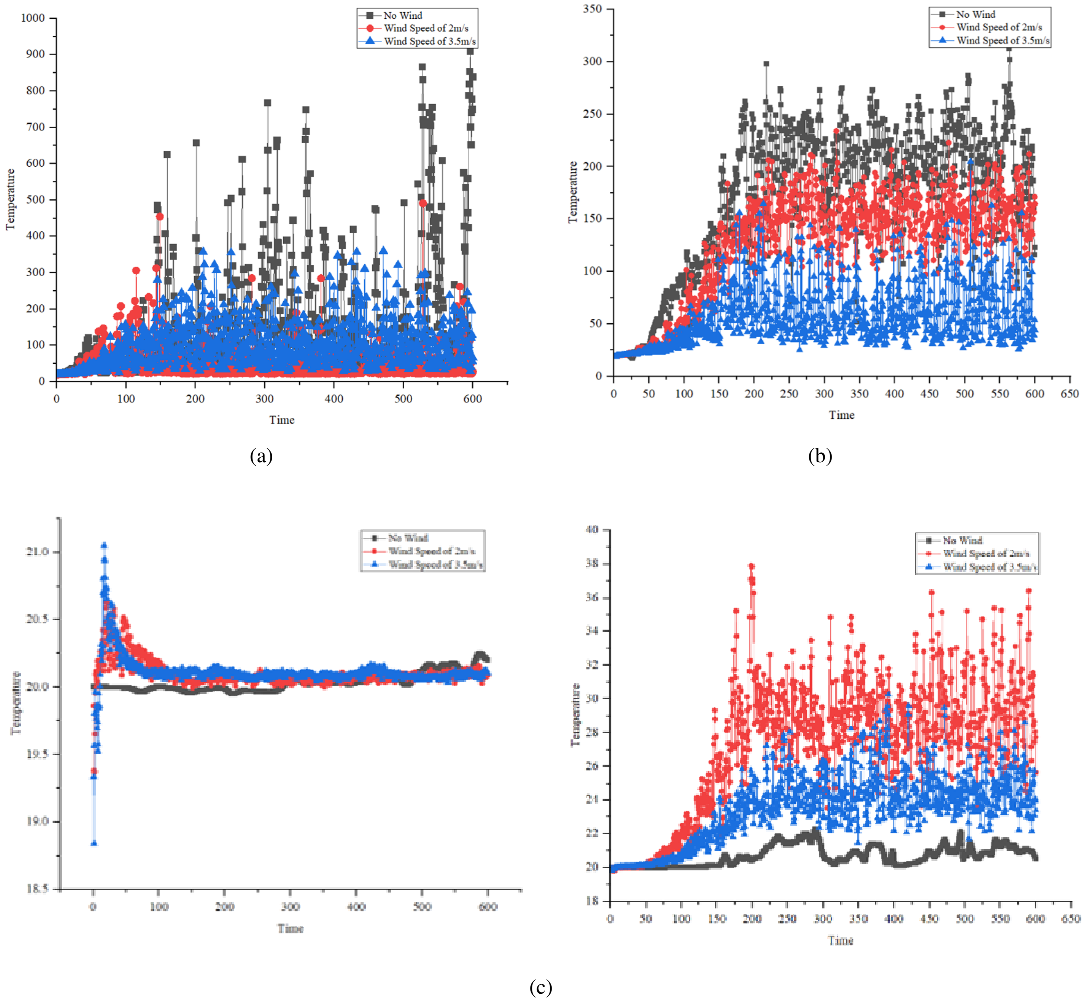


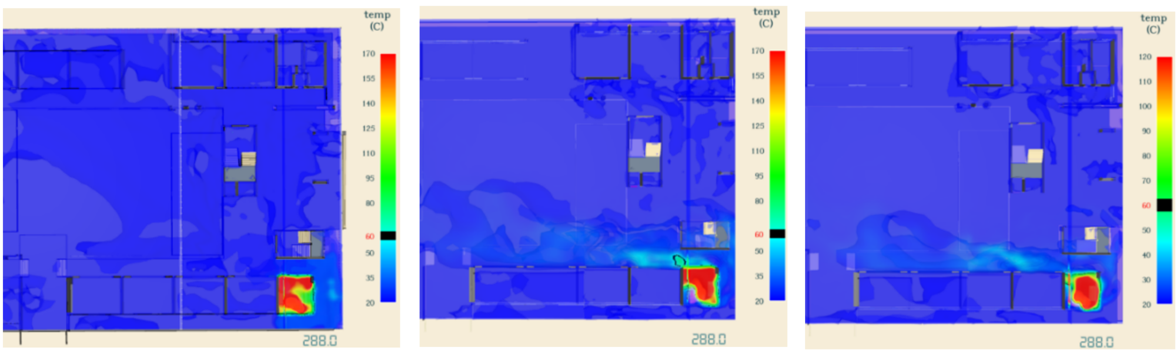
Figure 12. (a) Temperature variation chart of 1-D0 at different wind speeds on the first floor; (b) Temperature variation chart of 1-D00 at different wind speeds on the first floor; (c) Temperature changes of 1-D3 and 1-D4 at different wind speeds on the first floor

As shown in the subgraph (a) of Figure 12, the temperature fluctuation above the fire source in the first layer is most significant when there is no wind. The temperature starts to change around 35 seconds, gradually increasing from 20℃, reaching 200℃ within 2 minutes, and then gradually increasing and fluctuating, reaching a maximum of 929℃; the temperature change in a windless environment is higher than that at a wind speed of 3.5 m/s, and higher than that at a wind speed of 2 m/s. The highest temperature in a windless scenario can reach twice the highest temperature at a wind speed of 3.5 m/s, and the temperature at a wind speed of 2 m/s is more concentrated in the range of 20-120℃. This indicates that above the fire source, with the increase of wind speed, heat can be rapidly dissipated and burned to a certain extent. However, when the wind speed reaches a critical value, a heat flux may form with the increase of wind speed, moving slowly, resulting in a decrease in temperature dissipation rate.

From the subgraph (b) of Figure 12, it can be seen that the temperature change at the entrance of the fire source room shows a significant stratification with the change of wind speed. That is, the average temperature at this location without wind is greater than the average temperature at a wind speed of 2 m/s and greater than the average temperature at a wind speed of 3.5 m/s. As the wind speed increases, the temperature decreases, and the temperature ranges are concentrated at 175-275℃, 100-200℃, and 25-100℃, respectively. That is, a certain distance from the fire source will be affected by the temperature released by the combustion heat of the fire source, and the temperature will change significantly with the increase of wind speed. This indicates that the heat is greatly affected by the wind speed during the dissipation process.

As shown in the subgraph (c) of Figure 12, in the three working conditions, when a fire occurs on the first floor, the temperature at Exit T3 remains almost unchanged. Although Exit T4, which is closest to the fire source, is affected by the fire and causes an increase in air temperature, the highest temperature is 38℃. In terms of temperature, it will not affect personnel evacuation. Therefore, in practical situations, only the visibility of smoke and the value of harmful gases in the air need to be considered to ensure personnel safety; the temperature at the T4 port is the lowest when there is no wind, and it has started to fluctuate slightly in the past 3 minutes, changing within a range of a few degrees. This indicates that heat flows around in the absence of wind and is also lost over time; at a wind speed of 2 m/s, the heat flow moves faster and there is more heat flowing towards the T4 port under the influence of wind direction, resulting in an increase in temperature. The temperature at the T4 port at a wind speed of 3.5 m/s is lower than that at 2 m/s, as higher wind speeds result in greater heat transfer and loss. In summary, in the presence of natural wind in the external environment, wind speed generally accelerates the flow of combustion heat and reduces the temperature near the fire source, but it can also quickly cause changes in the surrounding air temperature, especially in more enclosed areas.

In order to better assess the situation around the T4 exit, taking 288s as the temperature slice value point, the temperature flow slices of the surrounding environment of the fire source room under three working conditions can be obtained as follows:



(a) (b) (c)

Figure 13. (a) No wind; (b) 2 m/s wind speed; (c) 3.5 m/s wind speed

Using 60℃ as the temperature slice boundary, it can be seen from the graph that at the same time, when there is no wind, the temperature flow diffusion is slow, mainly concentrated in the fire source and enclosed room. As the wind speed increases, the temperature flow direction moves. From the subgraph (b) of Figure 13 and the subgraph (c) of Figure 13, the temperature boundary can be seen. At the 288 th second, the temperature at the entrance of the room and the adjacent corridor has reached 60℃, reaching the short-term tolerance value of the human body. However, as the combustion continues, the temperature will still remain within this range. Therefore, T3 and T4 ports should not be used as evacuation exits, further indicating that an increase in wind speed will accelerate the flow velocity of smoke and the diffusion space of temperature.

Export the temperature curves of each measuring point at three different wind speeds from the Pyrosim simulation results, as shown in Figure 14.

By comparing and analyzing the temperature curves, it can be seen from the subgraph (a) of Figure 14 that the temperature above the three-layer fire source decreases significantly with the gradual increase of wind speed, indicating that wind speed has a great effect on the heat dissipation of combustion materials; From the subgraph (b) of Figure 14, it can be concluded that the temperature at the entrance of the fire room is highest in the absence of wind, concentrated between 200-250℃, while in the presence of wind, the temperature at the entrance of the room is basically 50℃ or below. This indicates that the presence of natural wind from the outside can dissipate heat within a small distance, thereby reducing the impact on the surrounding environment; The temperature at the T3 and T4 entrances closest to the fire source on the third floor will not exceed 35℃ throughout the fire, mainly concentrated around 20-30℃, so it will not affect evacuation.

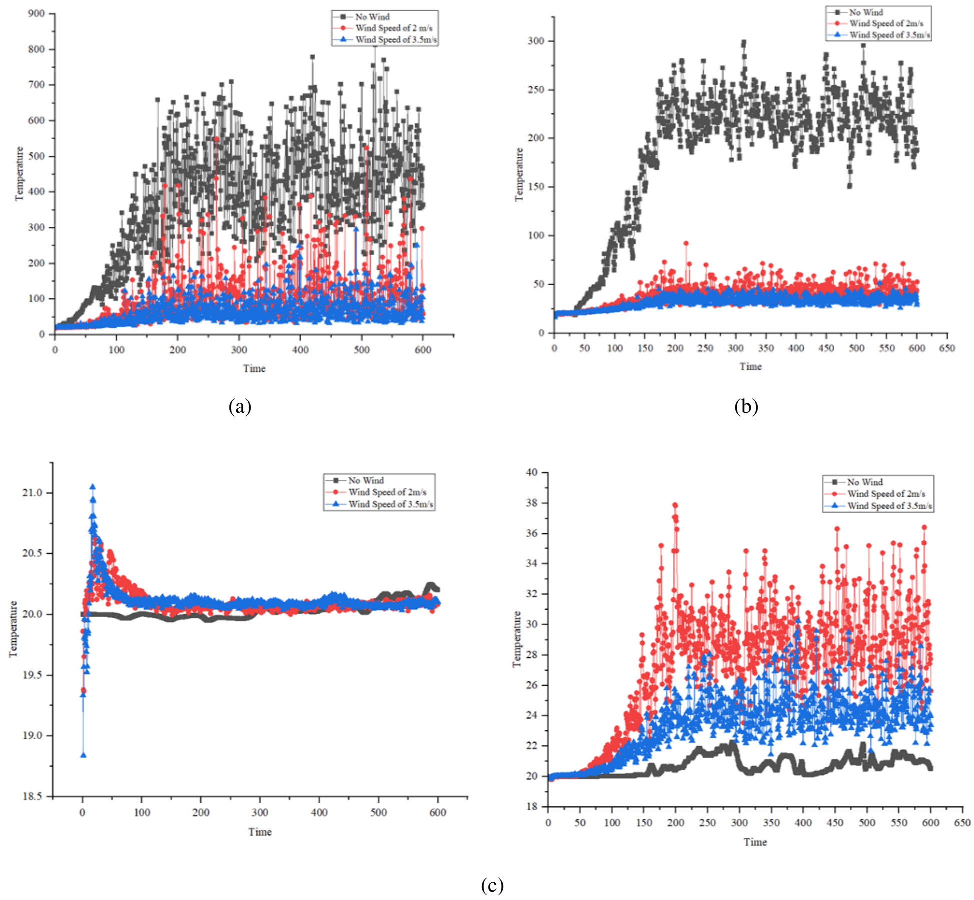


Figure 14. (a) Three layer 1-D0 temperature change chart; (b) Temperature variation diagram of Layer 1-D00; (c) Temperature variation diagram of layer 1-D3 and 1-D4

In summary, under windless conditions, the heat accumulation above the fire source is most significant. Due to the inability to dissipate heat quickly, the temperature rises sharply and reaches extremely high levels. This high-temperature environment poses a serious threat to the safety of personnel's lives. Under low wind speed conditions (such as 2 m/s), the wind begins to dissipate heat, taking away heat from the source of the fire, resulting in a slower rate of temperature rise and limiting fluctuations within the high temperature range. This indicates that an appropriate increase in wind speed can help reduce the temperature above the fire source. Under high wind speed conditions (such as 3.5 m/s), the effect of wind is more significant. The heat is quickly carried away, resulting in a reduced range of temperature fluctuations, but it may form a heat flux that affects the rate of temperature dissipation. However, overall, high wind speeds still help to lower the temperature near the fire source.

(2) Analysis of temperature curves at different measurement points on different floors under the same wind speed

From the comparison between the subgraph (a) of Figure 12 and the subgraph (a) of Figure 14, it can be seen that as the floor rises, the temperature above the fire source will be higher in the absence of wind than in the presence of wind, further indicating that the flow and dissipation of combustion heat and temperature are accelerated under the influence of wind; At a wind speed of 2 m/s, the temperature above the fire source on the first floor is concentrated at 10-130℃, while the temperature on the third floor fluctuates rapidly at 20-200℃. At a wind speed of 3.5 m/s, the temperature above the fire source on the first floor fluctuates rapidly at 30-200℃, and the temperature on the third floor fluctuates rapidly at 20-90℃. It can be seen that the rise of the floor can accelerate the temperature fluctuation in the presence of wind, which is due to the influence of air pressure and floor ventilation. However, it does not always meet the requirement that the temperature range above the fire source on the third floor will be lower than the temperature at its location on the first floor. As shown in the temperature comparison chart above the fire source, the temperature on the third floor is higher than that on the first floor at a wind speed of 2 m/s, but at a temperature of 3.5 m/s, the temperature on the third floor is ? The impact of height on temperature will only be significant at this time. From the comparison between the subgraph (b) of Figure 12 and the subgraph (b) of Figure 14, it can be seen that as the floor increases, the wind speed has a significant impact on the ambient temperature at a certain distance from the fire source. As the wind speed increases, the temperature tends to decrease, and the temperature changes on higher floors are more pronounced; the staircase entrances of T3 and T4 are far away from the fire source, and heat is lost during the process of smoke propagation. Therefore, as shown in the subgraph (c) of Figure 12 and the subgraph (c) of Figure 14, their temperature is always below 60℃, which will not affect the crowd in terms of temperature. Moreover, under the same working conditions, such as no wind or wind, the fluctuation of the staircase entrances on the third floor is greater than that on the first floor, further indicating that the rise of the floor will increase the impact of the external natural wind variable on the fire temperature.

From the above, it can be concluded that the T1 staircase exit exhibits stability under various working conditions and is an ideal evacuation route; The T2 staircase entrance is susceptible to high wind speeds and is not the preferred evacuation exit; The T3 staircase provides a certain evacuation time window (about 2 minutes) in calm conditions, but rapidly deteriorates in windy conditions; although the T4 staircase entrance is close to the fire source, it can provide a certain amount of evacuation opportunity under certain conditions (such as no wind and window angle influence). The simulation results also show that the temperature around evacuation exits at a certain distance is less affected by fire sources and is usually kept within a safe range (below 60℃). This is crucial for the safety of personnel evacuation, as high temperatures may affect the health and safety of people during the evacuation process. Floor height is one of the key factors determining temperature distribution. As the floor rises, the temperature above the fire source shows a downward trend to some extent. This may be due to the influence of air pressure and floor ventilation, which makes it easier for heat to be carried away in high-rise buildings. However, this downward trend is not consistent, as floor height may also affect the path and speed of airflow, thereby affecting the distribution of temperature. In building fires, the impact of floor height on temperature should be fully considered. For high-rise areas, although the temperature may be relatively low, vigilance should still be maintained as there may be other risk factors such as smoke accumulation and restricted escape routes.

4 Conclusions

This article uses the i-WRBS method to identify and extract fire risk factors, uses the DEMATEL method to clarify potential key risk factors of fire, and uses Pyrosim software to complete numerical simulation. The results show that external environmental variables such as wind direction and wind speed will have a significant impact on fire rescue and evacuation processes. The conclusions drawn from the simulation results are as follows:

(1) Evacuation path selection: When there is no wind or low wind speed (such as 2 m/s), stairwells far away from the fire source (such as T1 and T2 stairwells) are safer, and stairwells near the fire source (such as T3) have slower smoke diffusion, but can still affect visibility for a long time. Emergency evacuation needs to be carried out in the early stages of the fire. When the wind speed increases to a certain extent (such as 3.5 m/s), smoke quickly spreads to the staircase entrances of T2, T3, and T4, significantly shortening the effective evacuation time, especially in the downwind direction. The evacuation path in the crosswind or upwind direction should be prioritized. The staircase entrance near the fire source is directly affected by smoke, and the degree of influence is higher. The fluctuation of smoke at the lower staircase entrance is relatively large, and the increase in wind speed will intensify the fluctuation of smoke height, increasing the uncertainty of smoke diffusion. Its evacuation potential needs to be analyzed based on actual conditions (such as wind speed, wind direction, window opening status, etc.).

(2) The influence of floor height: The smoke diffusion speed of high floors is relatively fast, especially when the wind speed is high, the visibility of smoke decreases rapidly, and special attention should be paid to the smoke diffusion of high-rise buildings.

(3) The influence of wind speed on temperature distribution: In the absence of wind, the temperature above the fire source changes significantly, with a wide fluctuation range and overall high temperature; Under windy conditions, as the wind speed increases, the temperature fluctuation range above the fire source decreases, and the overall temperature tends to decrease, indicating that wind speed can effectively promote the diffusion and dissipation of heat. As the number of floors increases and there is no wind, the temperature above the fire source usually gradually decreases; Under windy conditions, the temperature difference between floors may increase or decrease depending on the intensity and direction of wind speed. Therefore, in general, the temperature fluctuations on higher floors are more significant, indicating that the impact of external wind speed on the temperature of higher floors is more pronounced.

This study provides a basis for the fire safety management of public teaching buildings to a certain extent, especially in the optimization of personnel evacuation routes, the design of fire warning systems, and the configuration of high-rise fire-fighting facilities. In practical applications, sensitivity to wind direction and speed variables can be increased during initial fire control and rescue stages based on changes in wind speed and fire source location, which helps to adjust efficient evacuation strategies and enhance safety during fires. These rules have important guiding significance for fire safety prevention and emergency response in teaching buildings, and provide some inspiration for the evacuation routes of floor personnel, so as to effectively allocate people to escape and minimize possible fire hazards.

Author Contributions

He Hongjun: Primarily responsible for constructing the methodology, collecting and organizing data, as well as drafting the initial manuscript. Zhou Zhaohong: In the initial stages of the project, he was responsible for conceptualization; during the subsequent writing process, he conducted meticulous reviews and edits. Sun Yunbin: Focused on research related to fire simulation. Li Qiang: Responsible for organizing and conducting expert interviews and field interviews.

Funding

This research was supported by the following funds: (1) National Social Science Fund Project (Project No.: 20BJY144): This fund provided significant financial support for the conduct of the research, ensuring the smooth progress of the project. (2) China Foundation (Grant No.: 72361013): This fund provided necessary financial support for specific aspects of the research. (3) Jiangxi Provincial Department of Education Science and Technology Project (Project No.: GJJ2200530): The funding from this project provided a good research environment and conditions for the implementation of the research.

Data Availability

The data involved in this research will be provided upon request. If needed, please contact the authors, and we will endeavor to provide the relevant data to facilitate verification and extension research by other researchers.

Conflicts of Interest

The authors declare that they have no known financial interests or personal relationships that could have appeared to influence the work reported in this study. All authors conducted the research and wrote the paper with an objective and impartial attitude, ensuring the authenticity and reliability of the research.

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