fire

Article

Fire-Spread Characteristics and Evacuation Plan Optimization of Old Style Multi-Story Student Apartments

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Abstract: Fire is a major disaster event that can have a significant effect on public safety and social development. In a college or university, fire can seriously threaten the safety, lives, and property of those there due to the compact layout of apartment buildings and high population density. The ecological safety and sustainable development of buildings are also affected. In this study, PyroSim and Pathfinder software (version 2019) were used to simulate and analyze fire-spreading characteristics based on a multi-story university student apartment building. Additionally, the most effective safe evacuation plan from four fire evacuation drill schemes was identified by analyzing and comparing their performance. Results show that the spreading of fire smoke on different floors is significantly affected by the roof structure and the vertical and horizontal diffusion characteristics of smoke. While the smoke layer at the evacuation stairways has little effect on a safe evacuation, poor visibility due to smoke and ceiling temperatures has a significant effect. Safe evacuation becomes progressively more difficult at different floor levels from the top to the bottom of the building. The optimal safety scheme involves orderly evacuation through two open emergency exits. The number of emergency exits has a significant impact on the evacuation effectiveness. Measures and suggestions have been proposed to deal with apartment fires that address pre-event prevention, emergency loss reduction during the event, and post-event report-back. These proposals form an important theoretical reference for emergency evacuation and student apartment fire safety, providing important guidance for ecological safety protection of buildings and sustainable development.

Keywords: apartment fire; smoke spread; safe evacuation performance; building ecological safety; sustainable development

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1. Introduction

Fire is a type of major disaster that most frequently and universally affects public safety and social development [1]. With the promotion and development of higher education, colleges and universities continue to increase enrollment, and the number of resident students continues to rise. Accommodation space generally does not increase at the same pace, increasing the density in student apartments [2]. Meanwhile, many university buildings have inadequate hardware facilities, incomplete fire protection facilities, imperfect fire emergency systems, and structural designs that are inappropriate for satisfying the current student numbers situation due to their age [3]. Additionally, some colleges and universities have poor management. Safety awareness in teachers and students is ignored, and they close and lock the safety exits of apartments for management convenience. Additionally, teachers and students illegally park electric vehicles or store items in the stairwells of apartment buildings, blocking safety passages and exits, which increases the difficulty of ensuring safe fire evacuation [4]. The development of the internet has increased student use of electronic equipment considerably, increasing the electrical power demand in student dormitories. To overcome this, some students make illegal electrical connections or smoke in the dormitory, increasing the chances of starting a dormitory fire [5]. In addition, a large number of flammable materials, such as bedding and clothing, are stored in limited spaces, creating favorable conditions for starting and accelerating the spread of fires. Furthermore, many teachers and students have a poor awareness of the need for fire protection and do not understand where fire protection facilities are located, or how they should be used. This makes it difficult for them to react appropriately at an early stage to ensure their safe evacuation [6].

According to statistical data from the National Fire and Rescue Administration in 2021, 32,000 fires occurred in schools and other densely populated areas [7], resulting in 422 injuries and 179 deaths. Student apartment buildings are difficult to evacuate once a fire has started, due to their high density, making them extremely dangerous. Therefore, an investigation into safe evacuation during a fire in an old multi-story student apartment building is critical to ensuring the safety of students and the sustainable development of building ecology.

There have been many studies conducted on fire-spread in buildings and safe evacuation. For instance, in terms of traditional methods, Hao [8], Zhan and Chen [9] used Pathfinder software to conduct fire evacuation simulations for dormitory buildings, finding that the evacuation time increased with a decrease in the number of floors. Liang et al. [10] used Fire Dynamics Simulator software to simulate the fire scene in a university and found that the fire corridor on the same floor was more dangerous than the dormitory itself, noting that the risk decreased with increasing floor levels. Zou et al. [11] studied the characteristics of visibility due to smoke, ceiling temperatures, and the safe evacuation time, finding that the effectiveness of fire-fighting facilities and the closure of ignition points in dormitory buildings have a considerable impact on safe evacuation. Joakim et al. [12] used a questionnaire to study the sensory perception of different groups of people during the design of fire evacuation dissuasive signs, and relevant suggestions were proposed for sign designers. Miao [13,14] and Han et al. [13,14] analyzed the characteristics and influencing factors, such as building form and functions commonly existing in college dormitories, and then proposed fire prevention measures. Xu et al. [15] and Jia et al. [16] used a combination of BIM modeling and PyroSim to analyze the impact of changes in smoke visibility and other parameters of the evacuation process for different buildings, providing reference for evacuation design. Zhang et al. [17] first optimized the public areas of the subway, and then imported the BIM model into PyroSim to simulate fires in different locations. They used Pathfinder to conduct safety evacuation research, which showed that optimizing the layout can improve the efficiency of safety evacuation. Fu et al. [18] used PyroSim to simulate fires in confined spaces, exploring the variation patterns of different parameters under different working conditions. Based on the results obtained, they then proposed rectification suggestions for such places.

In terms of new methods, Gerges et al. [19] and Minji et al. [20] observed the impact of dynamic emergency clues on evacuation, and sent the evacuation instructions directly to the mobile phones of the evacuees through customization to intelligently find the best exit route for evacuation. Fang et al. [21] discussed the advantages and disadvantages of current intelligent fire evacuation by using the Internet of Things. They discussed the development opportunities of 5G technology in future building fire evacuations. Yen Chern et al. [22] designed and developed fire evacuation simulation software using a Belief-Desire-Intention agent plug-in, covering fire, building layout, human multi-agents, and other structural features. Lee et al. [23] proposed a fire evacuation simulation method that can convert Fire Dynamics Simulator fire-spread data into a unit structure and map it to a FFM, which can quickly calculate the evacuation situation under different fire conditions. The results approximate to the actual situation.

The above studies used traditional methods, such as PyroSim and Pathfinder software, or new technologies such as the Internet of Things and 5G to describe the problems of the fire-spread phenomenon and evacuation times. There are few in-depth studies into fire characteristics, such as horizontal and vertical diffusion of fire-spread, as well as the impact of poor visibility, ceiling temperatures, and other factors. Previous studies also failed to propose targeted and constructive advance prevention and improvement measures during and after a fire event.

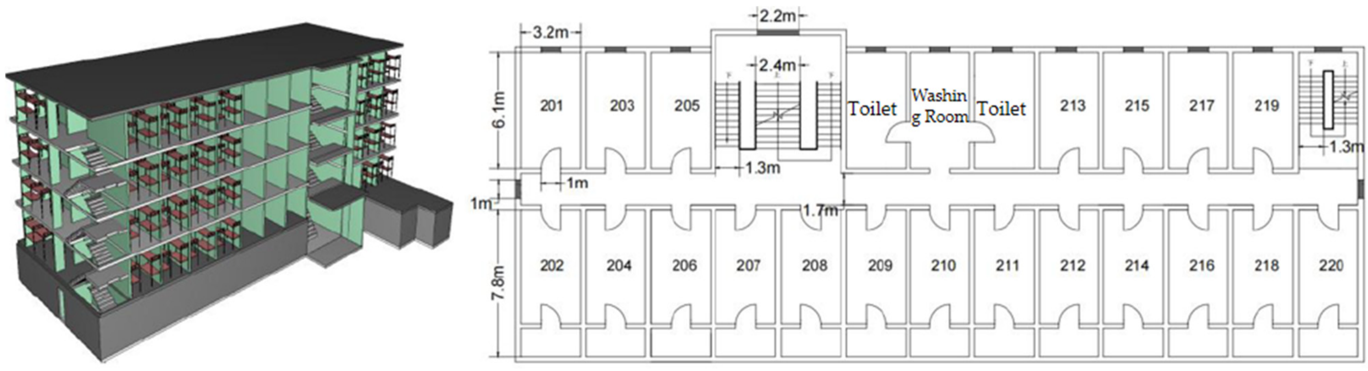
In this study, a multi-story student apartment building in a university in the Shandong Province was used as an example. PyroSim software was used to simulate the fire-spread characteristics (visibility due to smoke, ceiling temperatures, and smoke layer heights) on different floors, analyzing the diffusion characteristics of smoke spread during a fire and its impact on safe evacuation. Pathfinder software was then used to simulate and analyze the safe evacuation of personnel and compare the evacuation effectiveness of different safe evacuation plans to obtain an optimal evacuation plan after a disaster for the selected condition. Finally, measures were proposed for dealing with apartment fires in terms of the three dimensions of pre-prevention, emergency startup during a fire event, and post-event summary. These proposals can provide an important theoretical reference for the fire safety and emergency evacuation of college students from apartment buildings, and also provide important guidance for building ecological safety protection and sustainable development.

2. Characteristics of Fire Smoke Spread on Different Floors

Thunderhead Engineering simulation software PyroSim was used with Fire Dynamics Simulator software (version 2019) to investigate the current situation in a university student apartment building in Shandong, as an example [24]. The fire-induced smoke spread characteristics on different floors were analyzed to provide scientific guidance for safe evacuation.

2.1. Model Establishment and Parameter Determination

The student apartment building has five floors in total. The first floor is outsourced and not currently a student dormitory. It is completely isolated from the upper student dormitory floors. Therefore, this study did not investigate any fires on the first floor. The structure and number of rooms on floors 2–5 of the apartment building are the same. Each floor has 20 dormitories (rooms), 2 bathrooms, and 1 washroom, making a total of 92 rooms over the four floors. The floor height is 3 m, and the floor and wall thicknesses are approximately 0.25 m. Each floor is equipped with two evacuation staircases at the east and west sides, respectively, with widths of 1.3 m (minimum) and 2.4 m (maximum). There are six people resident in each room. Room 205 on the second floor (R2-205) is vacant and modified for use as a distribution room. In addition, each apartment building floor is equipped with fire-fighting equipment and smoke alarms in accordance with regulations. However, there are no fire sprinklers or smoke exhaust systems due to the age of the building. Figure 1 shows the overall 3D model of the apartment building and the layout plan of the rooms on the second floor.



(**a**) (**b**)

Figure 1. 3D modeling and 2nd floor layout of student rooms. (**a**) 3D model, (**b**) room layout.

When dividing the model into grids, empirical values are often used, which are related to the characteristic diameter of a fire flame D^* [25]. When the grid size is taken as 1/4 to 1/16 of D^*, the simulation accuracy increases [25]. The D^* value can be obtained using the formula [25] $D^* = \left(\frac{Q}{\rho_\infty C_P T_\infty \sqrt{g}}\right)^{\frac{2}{5}}$, where ρ_∞ is the air density (set to 1.2 kg/m^3 in this study), c_P is the air specific heat capacity (set to 1 KJ/(kg·K) in this study), T_∞ is the ambient temperature (set to 293 K in this study), and g is the gravitational acceleration (9.81 m/s). Finally, the grid of the model is determined to be 0.5 m $\times$ 0.5 m $\times$ 0.5 m, and the number of grids in the whole building is 162,656. It has been verified that this grid size is $D^*/4.2$, which meets the above grid modulus. Using the actual preliminary investigation and a similar literature analysis [26], the simulation time was set as 500 s, and the fire source reached the maximum heat release power within this time. The formula for the thermal power of the ignition source is [27] $Q = \alpha t^2$, where Q is the thermal release power of the ignition source (kW), α is the growth coefficient (kW/s^2), and t is the elapsed time since ignition (s). The thermal power growth coefficients depend on the type of combustible, each of which produce different types of fire [28]. Since most of the items in student dormitories are combustible, such as bedding, clothing, bed board and other fiber products, wood products, and book plastic, the individual item differences between the dormitories are ignored when building the model. They are uniformly set as bedding, clothing, and plastic products, and the walls are set as concrete structures. The combustibles of bedding, clothing, and plastic products assumed in this simulation can form fast fires that meet the reaction type characteristics of Class A solid material fires [29]. The growth coefficient is therefore set as 0.044 kW/s^2 in this study [30]. The time for the fire source to reach the maximum thermal power is calculated to be 386 s when the ambient temperature is set at 293 K. Based on the actual situation, the windows of each dormitory in the apartment are set to be scattered and half open. The safety exit of the ground floor is set to be open only on the west side and closed on the east side. The combustion of bedding, clothing, and plastic products produces carbon monoxide, carbon dioxide, and other toxic and harmful gases. Excessive concentrations of carbon monoxide and carbon dioxide can cause dizziness and headaches for personnel. Other toxic and harmful gases accumulate into smoke, and smoke is affected by the dimming and spreading of small particles of smoke, meaning the visibility in the combustion space decreases. According to previous studies and the literature review [31], combined with Table 1, it can be seen that dormitories are mostly independent small spaces. When the visibility of smoke at the safety exit is reduced to 5 m, it will be impossible to use the exit to evacuate safely.

Table 1. Critical visibility values for different spatial sizes [32].

Parameter	Small Space (Space Area Less than 100 m^2)	Large Space (with a Spatial Area Greater than 100 m^2)
Visibility (m)	5.0	10.0

2.2. Characteristics of Fire Smoke Spread on Different Floors

Fire incidents in distribution rooms may be triggered by many different factors, such as electrical overload, short circuits, unauthorized wire pulling, and aging of power cables during centralized electricity use. In student dormitories, however, fires are invariably triggered by single triggering factors such as open flames or electrical overloading. The distribution room is more prone to fire due to its normal mode of use and the materials and equipment stored there, and the consequences are often more serious than in dormitories. Room R2-205 has been renovated and established as the distribution room on Floor 2, and it is adjacent to the west side evacuation staircase. It is set as an ignition point for the analysis of fire-spread characteristics on Floor 2. Room R3-310, which is between the two evacuation staircases, was also set as an ignition point on Floor 3. Room R5-516, which has the worst air mobility (close to the east side evacuation staircase) was also set as an ignition point on

Floor 5. These three ignition points are used to compare the impact of different ignition points on the fire-spread characteristics in the student apartment building.

2.2.1. Analysis of Fire Smoke Visibility

Sensors were installed along the Z axis of the model 1.8 m above the floor of the three combustion floors (2, 3, and 5) to detect smoke and temperature distribution.

(1) Ignition point in R2-205

Two typical states, 172 s and 181.5 s after R2-205 ignition, were selected to visually observe the smoke spread and its impact on floor visibility compared to the visibility threshold due to smoke of 5 m.

In Figure 2, when R2-205 was on fire, the flue gas quickly spread to the exit staircases on both sides, and several rooms close to R2-205 were quickly filled with flue gas. The gas then rapidly spread to other locations through the narrow corridor, showing significant horizontal and vertical diffusion characteristics. After 172 s, the visibility, due to smoke near this room and at the east side (ECS) and west side (WCS) evacuation staircases, significantly decreased (Figure 2a) The visibility at the ECS evacuation staircase decreased to less than 5 m. As the WCS evacuation exit near the ignition point was on the side of the strong smoke flow, the smoke was able to spread up the staircase, quickly reducing the amount of smoke accumulation. However, when the fire continued to 181.5 s, the visibility here decreased to 5 m, as shown in Figure 2b, and the smoke spread was also aggravated at other locations to varying degrees. From that time, neither of the stairway exits were available for safe evacuation.

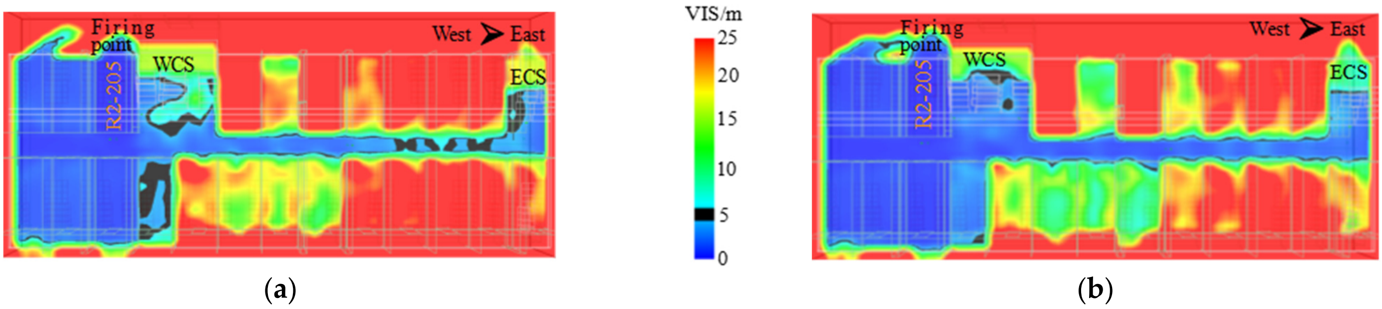


Figure 2. Smoke distribution with the visibility of R2-205 dropping to 5 m. (**a**) 172 s; (**b**) 181.5 s.

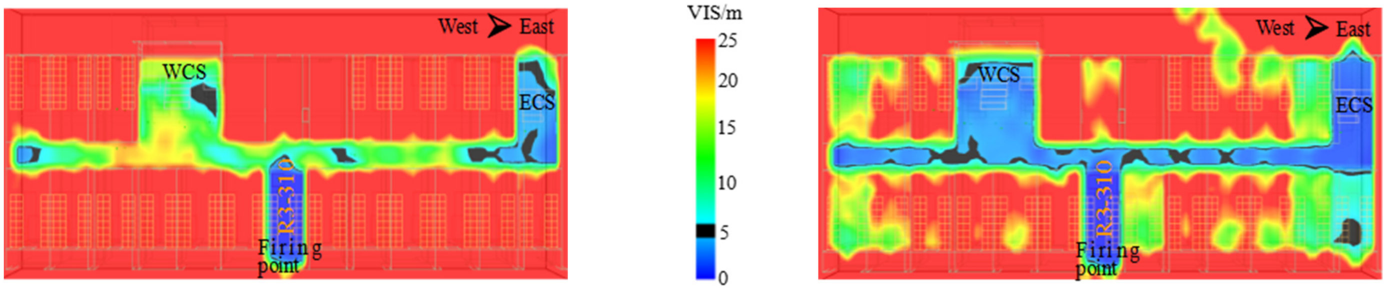
(2) Ignition point in R3-310

Similarly, using the visibility threshold, with smoke of 5 m as the benchmark, two typical states of 132.3 s and 181.2 s after R3-310 ignition were selected to visually observe the smoke spread and its influence on visibility.

As shown in Figure 3, compared with the combustion in R2-205, the smoke propagation due to R3-310 ignition only shows significant vertical diffusion characteristics. Figure 3a, at 132.3 s after ignition, shows that the fire smoke only spread along the corridor to the staircases on the two sides, and presented an obvious vertical upward spreading characteristic. Compared with the combustion process of R2-205, the influence of smoke convergence on the ECS was more significant than that on the WCS, and the smoke accumulated faster. The vertical diffusion of smoke to the ECS staircase was lower than that to the WCS. The visibility due to smoke at the ECS first dropped to 5 m at 132.3 s. The smoke then continued to spread horizontally and vertically, and the visibility on both sides continued to decrease. Some rooms were also affected by the smoke spread, and the visibility at the WCS also dropped to 5 m at 181.2 s, as shown in Figure 3b Neither staircase would be usable for evacuating safely from that time.

(3) Ignition point in R5-516

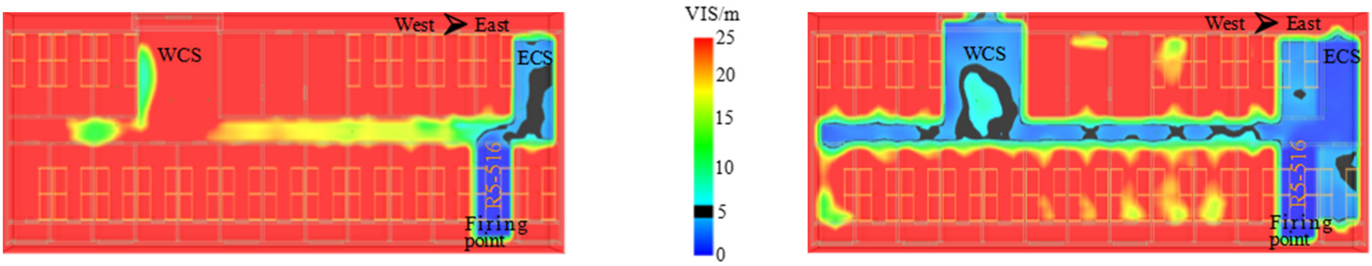
Similarly, two typical states, 112 s and 168.1 s after ignition in R5-516, were selected to visually observe the smoke spread and its impact on visibility when the visibility of this layer dropped to the threshold of 5 m.



(**a**) (**b**)

Figure 3. Smoke distribution with the visibility of R3-310 dropping to 5 m. (**a**) 132.3 s. (**b**) 181.2 s.

As shown in Figure 4, when the ignition point was located on the top floor, compared with the previous two conditions, its fire smoke could not continue to spread vertically upward, and it all accumulated in the free space of the top floor for horizontal diffusion. When the fire started in R5-516, the adjacent east corridor space was narrow and the ventilation condition less effective, resulting in more severe smoke accumulation. The visibility at the ECS decreased rapidly to 5 m after 112 s. The fire smoke then continued to spread along the corridor. After 168.1 s, the smoke accumulated at the WCS until the visibility was reduced to 5 m. Other rooms were less affected by the fire. From that time, the danger for safe evacuation of people on the top floor increased significantly.



(**a**) (**b**)

Figure 4. Smoke distribution with the visibility of R5-516 dropping to 5 m. (**a**) 112 s, (**b**) 168.1 s.

Hence, based on the visibility due to fire smoke index, there were significant differences in the fire smoke spread characteristics depending on where the ignition point was on each floor; however, the impact on the safe evacuation time was small (from 168–181 s). The safe evacuation time of the top floor was slightly shorter because there was no upward escape space for the smoke. Table 2 shows the similarities and differences of fire smoke-spread characteristics on different floors of the apartment building.

Table 2. Fire smoke spread characteristics on different floors.

Position	Characteristics of Smoke Spread	Safe Evacuation Time
Bottom floor (R2-205)	Significant horizontal and vertical diffusion: smoke quickly accumulates in adjacent rooms and staircases.	181.5 s
Middle floor (R3-310)	Significant vertical diffusion: staircases accumulate smoke rapidly, and other rooms largely unaffected.	181.2 s
Top floor (R5-516)	Significant horizontal diffusion: no upward escape space for smoke, which moves horizontally to staircases.	168.1 s

2.2.2. Analysis of Fire Ceiling Temperature

Ceiling temperature is another important factor affecting the safe evacuation of personnel during a fire incident [33–35]. According to the Chinese National Standard [30], and combined with Table 3, college students are generally adults. According to the formula for temperature and the maximum endurance time of the human body [36] ($t_2 = \frac{4.1\times10^8}{[(T_2-B_2)/B_1]^{3.61}}$), considering the impact of humidity on the human body in practical situations, a safety factor of 0.6 can be taken to obtain [36] $t_2 = \frac{2.46\times10^8}{T_2{}^{3.61}}$ (t_2 is the limit of human endurance time; T_2 is the air temperature; B_1 = 1, B_2 = 0). According to calculations, the maximum endurance time of the human body is 128.3 s at 328 K, 53.72 s at 343 K, 30 s at 353, and only 14.82 s at 373 K.

Therefore the ceiling temperature threshold was set at 333 K in this model, which was considered to be the maximum for the safe evacuation of personnel. Therefore, thermocouples were set at 1.8 m from the stair floor in the staircases to monitor the ceiling temperature at different times after ignition.

Table 3. The tolerance limit of the human body to high-temperature gases [36].

Temperature Conditions/°C	Humidity Conditions	Tolerance Time/min
<60	Moisture sufficiency	>30
60	Moisture content < 1%	12
100	Moisture content < 1%	1

(1) Ceiling temperature of R2-205 fire

The ceiling temperature was monitored and analyzed at both evacuation staircases (WCS and ECS) for up to 500 s after ignition, as shown in Figure 5.

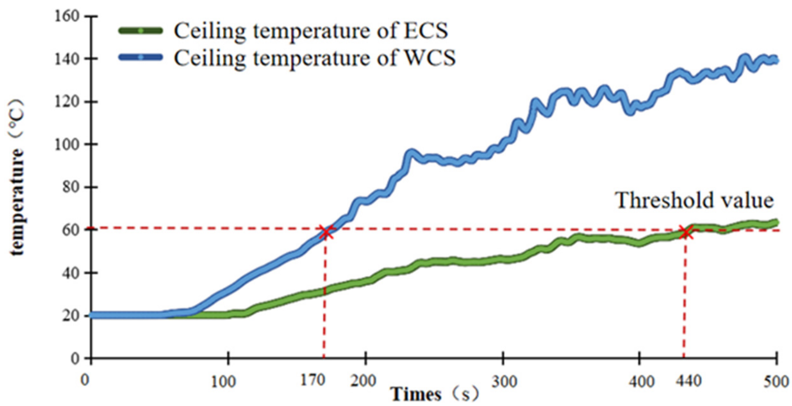


Figure 5. Variation in ceiling temperature at both staircases after R2-205 ignition.

In Figure 5, as the time after ignition increased, the ceiling temperature of both evacuation staircases increased continuously, albeit at different rates. When ignition occurred in R2-205, the WCS was relatively close to the ignition point, and it was slightly affected by the heat radiation and the energy transmission attenuation of smoke, causing the ceiling temperature to start to rise sharply after only 80 s. It reached the design critical value of 333 K after 170 s and continued to increase significantly; meanwhile, at the ECS, which was far from the ignition point, the heat of the smoke was lost and the ceiling temperature started to increase relatively slowly after 100 s. It reached the critical value after 440 s and reached the simulated final temperature of 338 K at 500 s; it also followed a relatively smooth development process. The ceiling temperature of the WCS therefore increased more significantly, affected by the location of the ignition point and the attenuation of smoke energy. The available safe evacuation time was only 170 s, while the time available at the ECS was 440 s.

(2) Ceiling temperature of R3-310 fire

Figure 6 shows the change in ceiling temperature at both staircases for up to 500 s after the ignition at R3-310.

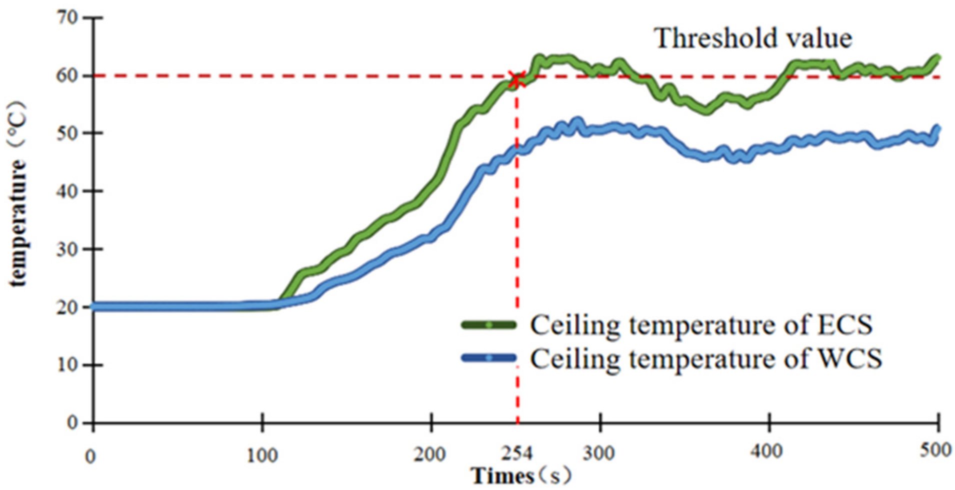


Figure 6. Variation in ceiling temperature at both staircases after R3-310 ignition.

When R3-310 was the ignition point, the temperature change trend and amplitude of the ceiling at both staircases were similar; both started linear growth after 100 s, and after approximately 250 s it fluctuated with a small amplitude before stabilizing. The ceiling temperature of the WCS did not reach 333 K during the whole 500 s period, while that of the ECS reached 333 K after 254 s before stabilizing at that level. The ceiling temperature of the ECS was always higher than that of the WCS, as the bottom safety exit (1st floor) on the east side was closed all year round. In addition, the ECS space was narrow, with less air flow; therefore, it accumulated heat more easily. On the other hand, the WCS had a larger space, and heat exchange was more frequent and easier to dissipate. Therefore, the ceiling temperature of the ECS reached the critical value ahead of the WCS, and the overall temperature of the ECS was approximately 10 K higher than that of the WCS. However, compared with the combustion of R2-205, the final state temperature of both sides was significantly lower after 500 s, with both fluctuating below 333 K. This may have been influenced by the significant vertical diffusion characteristics of the smoke layer so that the temperature could effectively diffuse to other spaces.

(3) Ceiling temperature of R5-516 fire

Figure 7 shows that, after ignition on the top floor, the change in ceiling temperature at both evacuation stairs was similar to that for the R2-205 fire, with some differences The figure shows that the slope of the variation curve was steeper, indicating that the temperature increased more sharply due to the influence of the structure space on the top floor. The ECS was close to the ignition point, and the ceiling temperature increased rapidly to 333 K after 195 s. The growth rate then continued to accelerate until the growth slowed down after 300 s. However, by then, the temperature had been at a very high level. The WCS was far from the ignition point, and it started to rise slowly after 150 s. However, it also reached 333 K after 330 s due to the influence of the small energy dissipation space on the top floor, and it continued to rise slowly. It reached the critical 333 K 110 s earlier than when the ignition point was in R2-205.

In summary, when the ignition point was located on different floors, it was affected by the energy diffusion characteristics of fire smoke and the floor space structure. Furthermore, the ceiling temperature was different at each evacuation staircase. When the fire was on the second floor (R2-205) and the top floor (R5-516), the near field evacuation staircase was more likely to reach the critical temperature, and the safe evacuation time was shorter, while the far field evacuation staircase took longer, which is conducive to safe evacuation. However, the evacuation time for top floor ignition was shorter than that at the second floor. The temperature of both evacuation staircases for the middle floor ignition (R3-310) was lower overall, and the evacuation time available was longer compared with the top floor fire, which was more conducive to personnel evacuation.

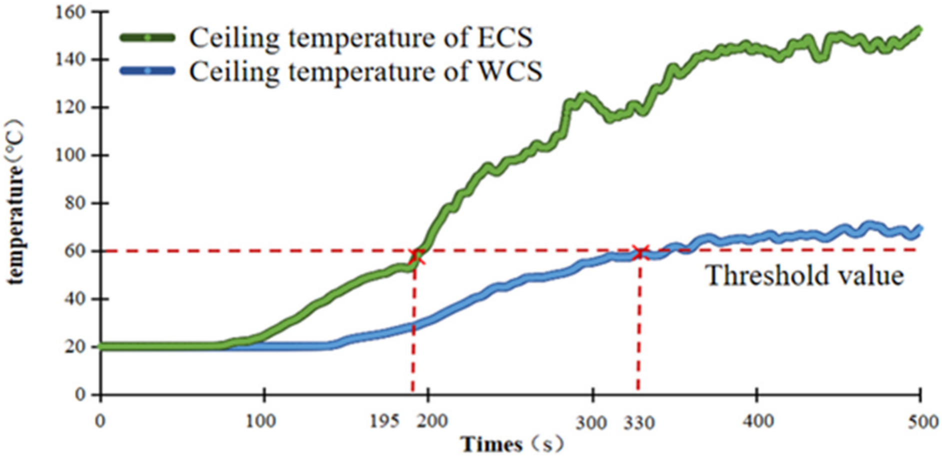


Figure 7. Variation in ceiling temperature at both staircases after R5-516 ignition.

2.2.3. Analysis of Fire Smoke Layer Height

When ignition occurs, a large amount of smoke is generated. Due to the small fire space, the smoke cannot be dissipated immediately and accumulates at the ceiling above the floor in a very short time. As the fire continues and develops, the thickness of the smoke layer increases and the height above floor level decreases. According to the Chinese National Standard [36], when the height of the smoke layer is less than 1.5 m, people cannot evacuate safely. Therefore, 1.5 m was set as the critical height parameter in this simulation.

(1) Height of smoke layer with R2-205 ignition.

The height of the smoke layer on the second floor at both evacuation staircases over the first 500 s after ignition is shown in Figure 8.

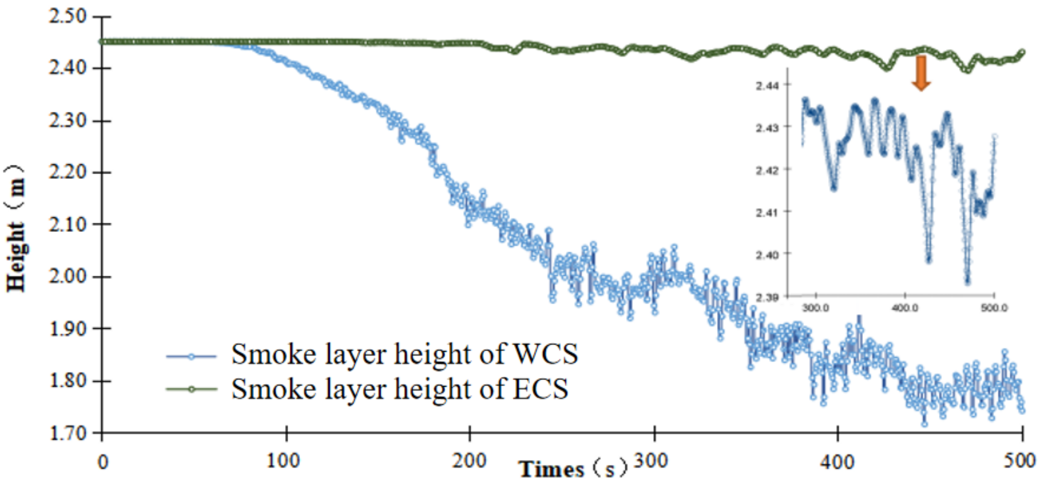


Figure 8. Variation in smoke layer height at both staircases after R2-205 ignition.

When ignition occurred in R2-205, the WCS was closest to the fire and was affected by the fire smoke, resulting in the smoke height starting to drop sharply after approximately 80 s. It continued to decline and tended to stabilize before 500 s, when the calculated final state was still 1.7 m (above the critical value of 1.5 m). Therefore, the WCS did not affect safe evacuation due to smoke height within 500 s. However, the ECS was further away from the fire and affected by the smoke diffusion. The smoke height was reduced slightly, and it remained well over the critical level; therefore, the smoke height did not prevent either staircase from providing safe evacuation within 500 s.

(2) Height of smoke layer with R3-310 ignition

As shown in Figure 9, when the ignition point was in R3-310, the smoke overflowed from the room and moved to the evacuation stairs on both sides through the corridor. The smoke height at both staircases followed similar patterns. The height at both started to decline suddenly after approximately 100 s. It then continued to decline slightly due to the influence of air flow and the vertical diffusion characteristics of smoke before gradually stabilizing. Finally, the smoke height of the ECS became stable at 2.1 m and that of the WCS at 2.25 m, both of which were higher than the threshold value, indicating that neither affected the safe evacuation once a fire started. In addition, the smoke height of the WCS was always significantly higher than that of the ECS., This was because the ECS space was smaller and the amount of diffusion and loss was less than at the WCS, resulting in more smoke accumulation, while the smoke height was significantly reduced.

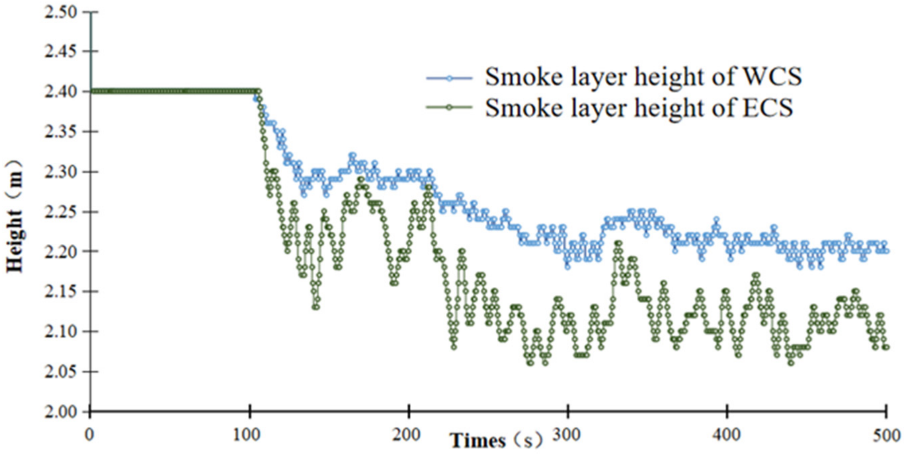


Figure 9. Variation in smoke layer height at both staircases after R3-310 ignition.

(3) Height of smoke layer with R5-516 fire

As shown in Figure 10, when the ignition point was in R5-516, it was far from the WCS; however, the smoke height there continued to decrease with the continuous diffusion of smoke. It reached 2.26 m after 500 s, and therefore did not affect the safe evacuation. On the other hand, the ECS was close to the fire point and the ECS space was narrow. Additionally, the air mobility poor and the smoke could not diffuse vertically after accumulating. Therefore, the accumulated smoke increased above that for ignition in R2-205 and R3-310, which was manifested in the height being reduced to 1.5 m after 70 s. It then continued to decrease until it stabilized at approximately 1.4 m, seriously affecting the safe evacuation from the ECS.

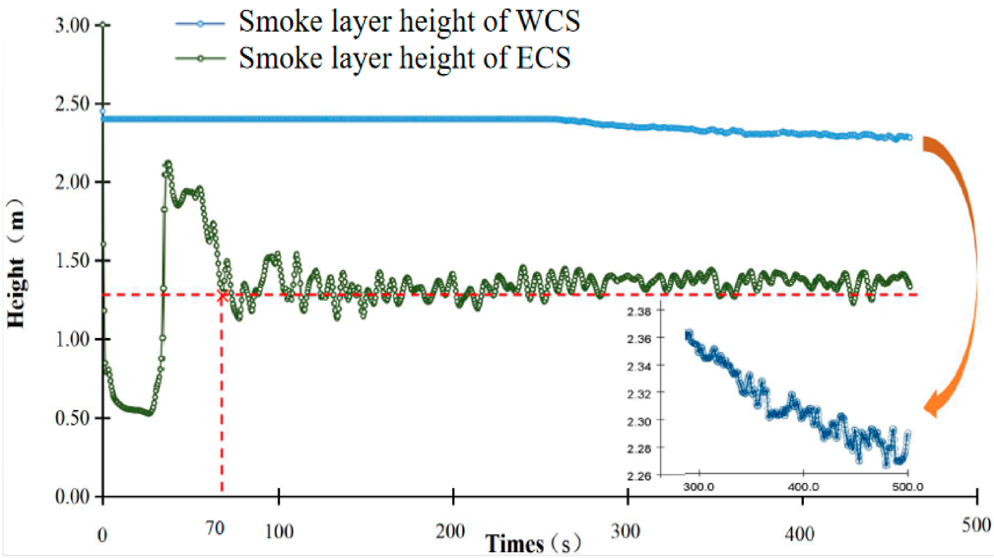


Figure 10. Variation in smoke layer height at both staircases after R5-516 ignition.

To summarize, the smoke height analysis shows that, under the three fire scenarios described above, only the top floor had a serious accumulation of smoke at the near-field evacuation staircase, with a considerable reduction in the height of the smoke layer due to the small space on the top floor available for vertical diffusion, which seriously affected the chances of safe evacuation.

2.3. Analysis of Fire Smoke Spread Characteristics and Evacuation Safety

The influence of poor visibility due to smoke, ceiling temperature, and smoke layer height at the evacuation staircases on the fire-spread characteristics and safe evacuation are summarized in Table 4., based on the simulation of fire ignition on each of the three floors. The fire-spread characteristics were significantly affected by the roof structure of the apartment building and the vertical and horizontal diffusion characteristics of smoke.

Table 4. Results of influence of three fire factors on spread characteristics and evacuation safety.

Ignition Point	Evacuation Staircase	Smoke Visibility		Ceiling Temperature		Smoke Height	
		Affected (√/×)	Start Time (s)	Affected (√/×)	Start Time (s)	Affected (√/×)	Start Time (s)
Bottom floor	East	√	172	√	440	×	
(R2-205)	West	√	181.5	√	170	×	
Middle level	East	√	132.3	√	254	×	
(R3-310)	West	√	181.2	×		×	
Top floor	East	√	112	√	195	√	70
(R5-516)	West	√	168.1	√	330	×	

Table 4 shows that safe evacuation was less affected by the smoke height but significantly affected by poor visibility due to smoke and ceiling temperature. As shown in Figure 11, using the ignition point in R5-516 as an example, the evacuation passage was not affected by any factors within the first 70 s after ignition, and people could safely evacuate. However, the ECS was affected by the smoke height after 70 s, while the WCS was still available to be used for evacuation. After 112 s, at least one evacuation staircase was affected by the ceiling temperature or poor visibility due to smoke, which reduced the ability or made it impossible to safely evacuate. When the ignition time is between 168.1 s and 195 s, WCS is only affected by smoke visibility, while Ecs is affected by smoke visibility and smoke height. However, at this time, both evacuation stairs are unable to evacuate normally. This also indicates that the available evacuation time when a fire occurs in R5-516 is 168.1 s, so all personnel on that floor must be evacuated within this evacuation safety time.

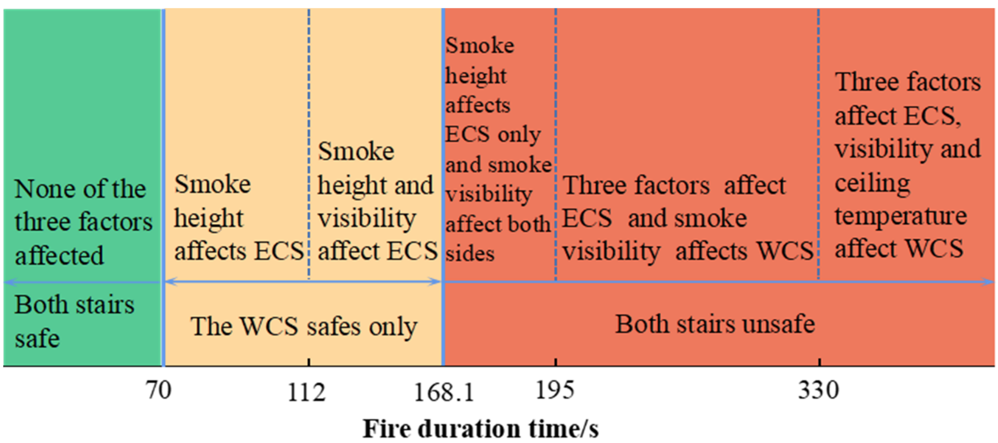


Figure 11. Impact of ignition in R5-516 on the safe evacuation performance.

3. Comparison and Optimization of Safe Evacuation Performance

3.1. Pathfinder Model Construction and Parameter Selection

3.1.1. Introduction to Simulation Software

According to the above analysis of fire smoke spread characteristics, the student apartment building has many rooms and a dense population, aspects which can have a substantial impact on safe evacuation in the event of a fire. The process of safe evacuation embraces the whole process, from fire ignition to the movement of people to an area that is removed from any fire threat. This is mainly determined by the available and required safe evacuation time [37]. Hence, to intuitively reflect whether people can be evacuated safely, this section describes the building of a Pathfinder evacuation model. In addition, evacuation routes and times are analyzed by customizing the number, speed, and evacuation behavior of personnel. This is then combined with computer graphics simulation and 3D role modeling [38].

3.1.2. Simulation Parameters Setting

The Pathfinder software is compatible with the AutoCAD® and PyroSim model file formats and can import PyroSim models directly. Using the situation of the apartment building described in Section 2, the model was directly imported and rooms and floors were divided, while doors, stairs, emergency exits, etc. were set up and the visibility due to smoke, temperature, and other parameters obtained from the PyroSim simulation were imported, resulting in a close approximation to the actual fire situation.

Because the research object is a male apartment building, the male height follows the normal distribution N (170, 4) (unit: cm), with the maximum height being 190 cm and the minimum 165 cm, with 42 cm shoulder width. The disorderly and orderly movement speeds are 1.4 m/s and 1.7 m/s, respectively [39]. The fire was simulated in daytime. Each dormitory can accommodate a maximum of six people; however, people are continually coming, going and washing. Therefore, four people are randomly arranged in each dormitory, six people are arranged in the corridor, eight people are arranged in the washroom, and one person is on duty at the exit of the first floor, totaling 379 people in the dormitory building.

The characteristics of human behavior are set as moving to the nearest safe evacuation staircase immediately or after a certain time. The time follows the normal distribution N (35, 5) (unit: s). According to the 3σ principle, 99.74% of the people start to evacuate according to the normal distribution N (35, 25) (unit s), and 0.26% of the people start to evacuate directly [40]. To simulate the congestion phenomenon caused by human congestion, when evacuation congestion occurs, the diameter of the personnel cylinder becomes 70% of the set diameter, meaning that the diameter reduction factor to prevent congestion is 0.7. Figure 12 shows the 3D evacuation model built by Pathfinder.

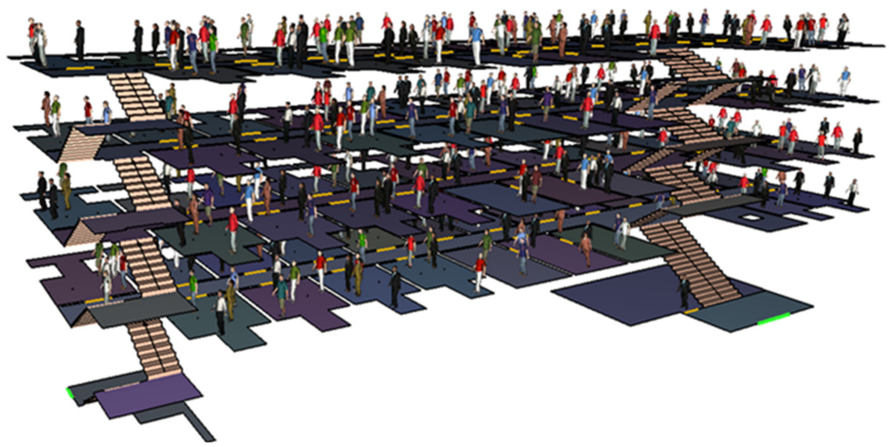


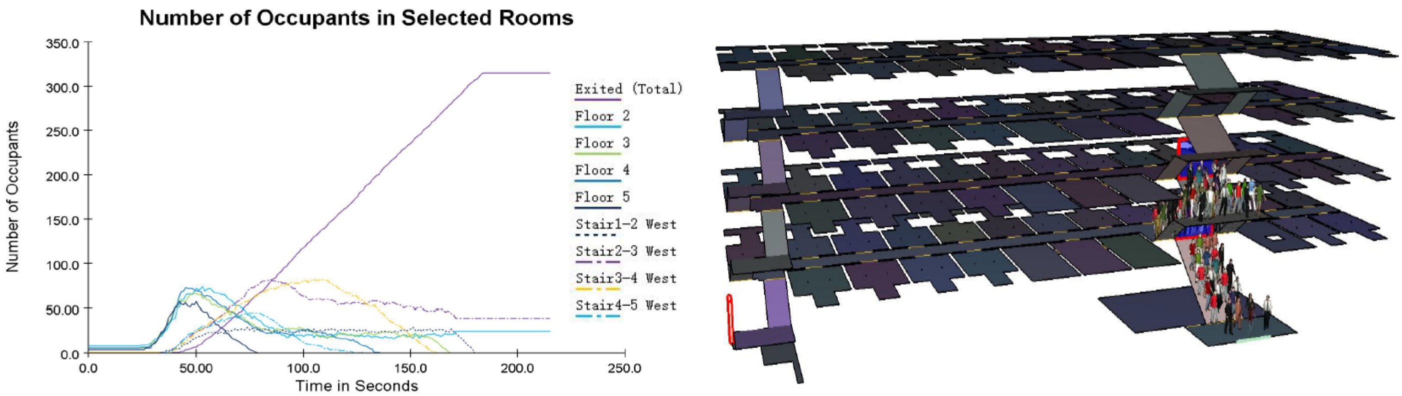
Figure 12. 3D evacuation model built by pathfinder.

3.2. Evacuation Capacity Analysis for Different Floors

In the previous section, the safe evacuation time through the staircases depended on the fire ignition point. In this section, the simulation analysis as to whether the apartment personnel can complete a safe evacuation is conducted based on the design conditions of the three floors above. The simulation of each working condition was repeated 10 times to improve the accuracy of the simulation results, and tthe number of people safely evacuated and the number of people remaining on the staircases within the safe evacuation time of each plan were monitored. Data with large deviations were eliminated, and its average value was used to analyze the ability to evacuate people.

(1) Evacuation analysis with R2-205 ignition

The safe and unsafe evacuations were monitored separately, and the statistical results are shown in Figure 13a, where the Exited (Total) represents the total number of people safely evacuated, Floor *i* (*i* = 2, 3, 4, and 5) represents the number of people remaining on Floor *i* after the safe evacuation time has been reached, and Stair (*j* – *j* + 1) (*j* = 1, 2, 3, and 4) represents the number of people remaining on the staircases between Floor *j* to *j* + 1.



(**a**) (**b**)

Figure 13. Analysis of safe evacuation performance after R2-205 ignition. (**a**) Number of people per location, (**b**) schematic diagram of evacuation.

Figure 13 shows that the people began to evacuate in a relatively short time and continued to transfer from each floor to the stairs, which showed that the change curve of the number of people on the staircases lagged behind that for those remaining on the floor. In addition, the floor characteristics of evacuation capacity show that the safe evacuation was faster for the higher floors. The complete evacuation of the fifth floor only took 78 s, while that of the fourth and third floors were 134 s and 165 s, respectively. According to the results in Table 4, the safe evacuation time of the WCS and ECS following R2-205 ignition was 170 s and 172 s, respectively. After 172 s, both staircases could not be safely used for evacuation; however, the stairs on other floors were available. Data statistics show that people on floors 3–5 and corridors, and stairs 1-2/3-4/4-5 could be safely evacuated after 172 s. The 315 people that are reflected by the Exited (Total) were safely evacuated, with only a few people remaining on Floor 2 (26 people) and stairs 2-3 (38 people). The above 64 people were not able to safely evacuate, as shown in Figure 13b If no emergency measures were taken, they would be affected by the fire.

(2) Evacuation analysis with R3-310 fire

As shown in Figure 14, after ignition in R3-310, the centralized evacuation and floor characteristics were similar to those for R2-205 ignition. Table 4 shows that the WCS and ECS were affected by fire smoke and temperature after 181.2 s and 132 s, respectively, but after 181.2 s, people on floors 3–5 and the corresponding staircases had been safely evacuated, and only a few people on Floor 2 and stairs 1-2 remained. However, because the fire smoke on this floor had significant vertical upward diffusion characteristics (Table 1), only Floor 2 and stairs 1-2 were located below Floor 3, and the delayed people who were still transferring would complete the safe transfer within 210 s, leading to 379 people in the whole building being completely transferred safely. Hence, based on the simulation scenario and parameters, ignition in R3-310 could complete the safe evacuation of all people, although there was no slack in the evacuation time (the complete evacuation of stairs 2-3 took approximately 180 s, which is equivalent to the actual safe evacuation time). If the occurrence of overcrowding or other adverse conditions is considered, there is the possibility of incomplete evacuation.

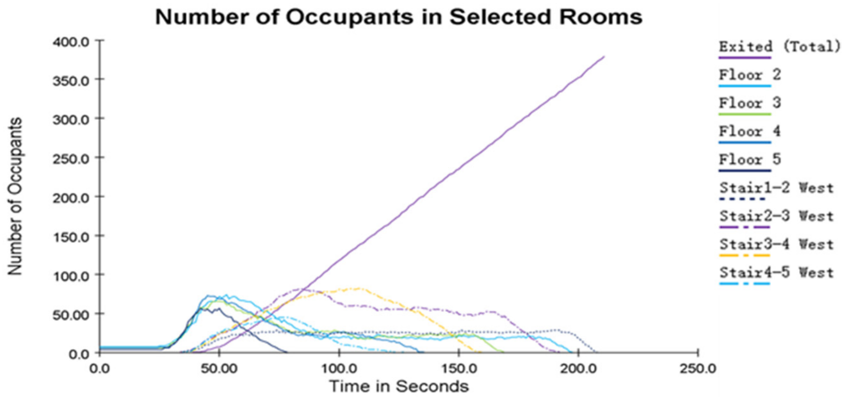


Figure 14. Analysis of safe evacuation performance after R3-310 ignition.

(3) Evacuation analysis with R5-516 ignition

Because the fire smoke has significant horizontal and vertical upward diffusion characteristics, the smoke and temperature have a relatively small impact on the bottom floor when the fire is on the top floor. Therefore, when simulating the top floor fire, the main investigation focuses on the people evacuation from the top floor (Floor 5) and its adjacent stairway (stairs 4-5). Evacuation below the fifth floor can be considered as successful. It can be seen from Figure 15 that it takes 70 s for people on Floor 5 to complete the evacuation, while the time for complete evacuation of stairs 4-5 is approximately 103 s, which is within the available time for safe evacuation (Table 2 shows that the safe evacuation time of stairs on the west and east sides is 168.1 s and 70 s, respectively). Finally, after 183 s, the statistics show that 379 people in the whole building completed the evacuation, indicating that, under this simulated working condition, in the event of a fire on the top floor, all of the people in the building can be evacuated safely.

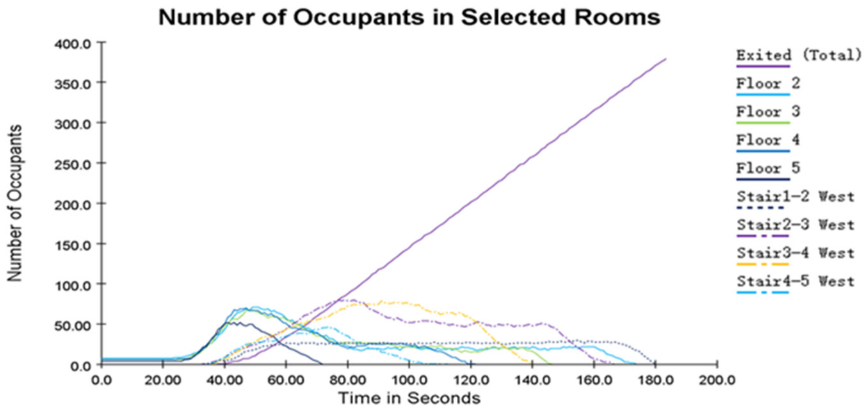


Figure 15. Analysis of safe evacuation performance after R5-516 ignition.

To summarize, for ignition on the middle (R3-310) and top floors (R5-516), all of the people can complete safe evacuation under design conditions. Some safe evacuation can be completed with bottom floor ignition (R2-205), which is shown by the increasing difficulty of safe evacuation when fire ignition changes from the top to the bottom of the building. The safe evacuation takes progressively longer (the complete safe evacuation time for ignition on floors 5 and 3 are 180 s and 210 s, however safe evacuation could not be completed for ignition on Floor 2).

3.3. Optimization Analysis of Safe Evacuation Drill Plan

In the above simulation scheme, the emergency exit at the bottom (first floor) of the east side is set to be closed, resulting in the safe evacuation of all people being unachievable. In fact, two important factors affecting safe evacuation are the number of emergency exits and whether evacuation is orderly. Hence, to ensure the fire emergency treatment and improve the evacuation efficiency, the number of emergency exits available must be considered, as should whether the evacuation is orderly. The evacuation emergency plan needs to be studied in advance and an optimal safe evacuation plan determined, as only then can the fire emergency plan and emergency path be determined, with a view to providing targeted prevention strategies after the fire.

Based on the above description analysis and the actual situation of the apartment building, in addition to considering the number of emergency exits (one or two) and whether the evacuation is orderly (orderly or disorderly), a total of four fire evacuation drill schemes were established, as shown in Table 5. The Pathfinder simulation software was also used to monitor and count the number of people evacuated and the evacuation time in each of the four schemes. This enabled the number of people still in the building and still transferring in the evacuation stairways to be determined for each scheme, as shown in Figure 16.

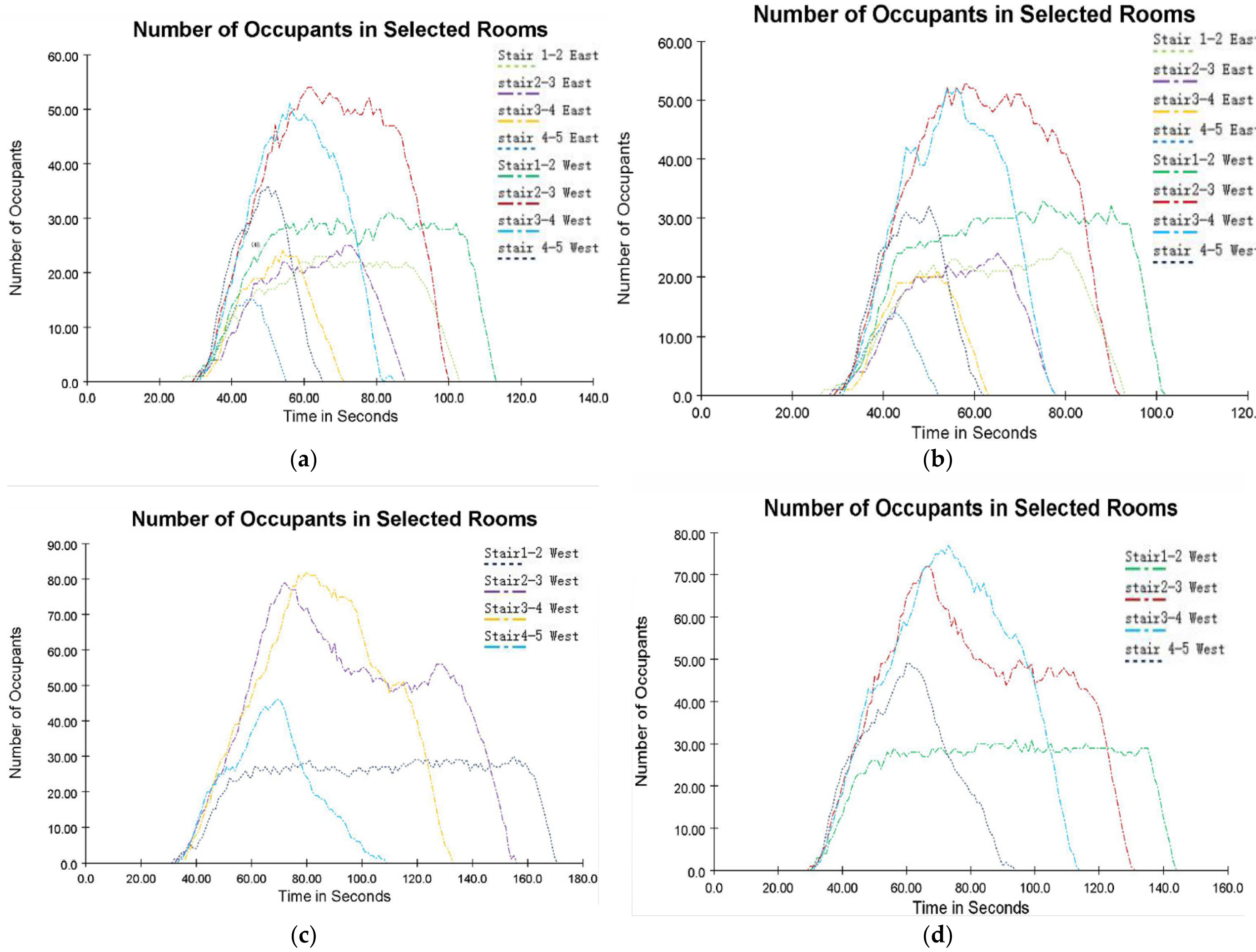
Table 5. Setting of fire evacuation drill plans.

Exercise Plans	Number of Exits	Orderly or Disorderly	Scheme Description
Plan 1 (P1)	2	Disorderly	Emergency exits at east and west of the first floor open, and people evacuated disorderly (E-W-N)
Plan 2 (P2)	2	Orderly	Emergency exits at east and west on the first floor open, and people evacuated orderly (E-W-Y)
Plan 3 (P3)	1	Disorderly	Only the west emergency exit open, and people evacuated disorderly (O-W-N)
Plan 4 (P4)	1	Orderly	Only the west emergency exit open, and people evacuated orderly (O-W-Y)

Notes: O-W: Only the west exit is open; E-W: East and west exits open. N: Disordered evacuation; Y: Orderly evacuation.

Figure 16 shows that, after the fire, the number of people in the evacuation stairway for each of the four plans changes in a similar way as the time after ignition increases, which is characterized by a rapid increase-flat-rapid decrease. This is due to the phenomenon of rapid accumulation-a large amount of accumulation or congestion-a rapid evacuation.

By comparing and analyzing Figure 16a,b, it can be seen that, when the emergency exits on both sides are open, the gentle phase of the change curve of the number of people in the orderly evacuation is significantly shorter than that in the disordered state, while the overall completion of the evacuation takes 104.7 s in the orderly state and 117.3 s in the disordered state. This indicates that the evacuation time is shorter for an orderly evacuation, which is more conducive to the rapid and safe complete evacuation of people. Similarly, comparing Figure 16c,d, the orderly evacuation is more conducive to safe evacuation; however, when only the west emergency exit is open (the simulation software is programmed to only open the west emergency exit by default, so that the best evacuation route is to transfer to the west emergency evacuation staircase), the evacuation times of the two plans are 175 s and 147.3 s, respectively. These times are much longer than when the emergency exits on both sides are opened, showing that the number of emergency exits has a significant impact on the success of safe evacuation. Therefore, the comparison analysis of personnel evacuation in the above four schemes shows that the evacuation time is the shortest when the emergency exits on both sides are open and orderly evacuation takes place. Hence, Plan 2 is the best one for evacuation and should be strengthened in the future.



Stair 1-2 West: WCS from floor 1st to 2nd
Stair 2-3 West: WCS from floor 2nd to 3rd
Stair 3-4 West: WCS from floor 3rd to 4th
Stair 4-5 West: WCS from floor 4th to 5th

Stair 1-2 East: ECS from floor 1st to 2nd
Stair 2-3 East: ECS from floor 2nd to 3rd
Stair 3-4 East: ECS from floor 3rd to 4th
Stair 4-5 East: ECS from floor 4th to 5th

Figure 16. Safe evacuation in four evacuation exercise schemes. (**a**) Plan 1: E-W-N, (**b**) Plan 2: E-W-Y, (**c**) Plan 3: O-W-N, (**d**) Plan 4: O-W-Y.

In Section 3.2, when ignition occurred in R2-205, not all evacuations could be completed safely. Using this condition as an example, the safe evacuation time after the fire was 172 s; however, according to the above four evacuation plans, Plan 3 only opens the west emergency exit and takes 175 s for disordered evacuation, which does not achieve complete evacuation. The other three schemes can achieve a completely safe evacuation, but the effect of improving the evacuation efficiency differs. As shown in Table 6, the evacuation efficiency of plans 1 and 2 has been improved by 31.8% and 39.13% compared with that of ignition in R2-205. The efficiency of Plan 4 has been improved by only 14.36%, which also indicates that opening the emergency exits and orderly evacuation are the best factors for ensuring safe evacuation. In addition, to obtain the importance order of the number of emergency exits and whether the evacuation is orderly, the effects on safe evacuation of varying the number of open exits, as well as orderly and disorderly exits were calculated and compared. It was found that the improvement to the evacuation efficiency of opening the second exit door was approximately 30% on average. The improvement of orderly over disorderly movements increased the efficiency by 15% at most, which is far less than the number of exit doors. This confirms that the impact of the number of safe evacuation exits is more significant than orderly evacuation, as shown in Figure 17. The above results also provide theoretical guidance for the improvement of safety awareness and measures in the apartment building.

Table 6. Performance improvement analysis of four drilling schemes based on R2-205 ignition.

Scheme	Evacuation Time (s)	Performance Improvement (%)	Notes
Plan 1	117.3	31.800	Suboptimal plan
Plan 2	104.7	39.130	Optimal plan
Plan 3	175	−0.017	Worst plan
Plan 4	147.3	14.360	Alternative plan
R2-205 Fire	172	0.000	Benchmark scheme

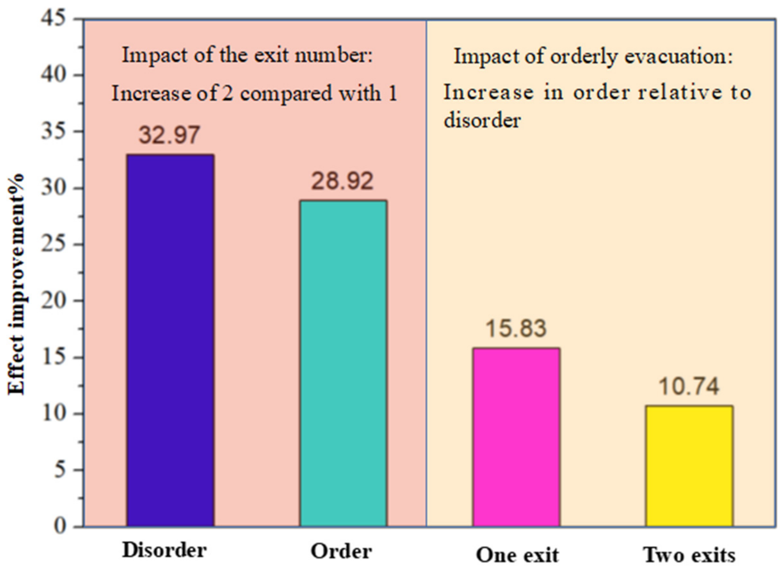


Figure 17. Importance comparative of number of emergency exits and whether evacuation is orderly.

To summarize, based on the actual apartment building situation and comparing the four evacuation drill schemes, the optimized plan 2 (open two emergency exits and orderly evacuation) has the best evacuation efficiency, and the evacuation effect is significantly improved by 39.13% for the planned R2-205 ignition. Meanwhile, it was found that the number of emergency exits has a more significant impact on the evacuation effect than whether the evacuation was orderly or not.

4. Proposed Fire Prevention and Evacuation Measures

It has been shown above that the evacuation time of a student apartment building is relatively short once the fire starts, which brings great challenges for the safe evacuation of students due to the high student density. Therefore, considering the time characteristics of fire development, fire prevention and evacuation measures are proposed in the three dimensions of pre-fire incident, during-fire incident, and post-fire incident, which is also a better implementation of the policy of "prevention first, prevention combined".

(1) Prevention measures

Optimize fire protection design and improve fire safety. This apartment building is an old building, and should therefore be updated with added mechanical smoke exhaust systems to reduce the diffusion of smoke inside the building, thus increasing the safe evacuation time [41]. Fire prevention measures such as smoke and temperature sensors and sprinkler systems should be added. The sensors can detect and sound an alarm timeously. Adding fire doors can establish separate fire compartments and limit the fire to finite elements. Adding to and inspecting firefighting equipment, such as fire extinguishers, and ensuring all staff learn how to use the equipment effectively is imperative, as is [42] improving the apartment building training and management systems, as well as the management, emergency, and psychological comfort of the management personnel [43].

Strengthen safety education and formulate safety emergency plan. The above results show that orderly evacuation is more conducive to the safe evacuation than disordered evacuation. Therefore, the property department should carefully consider the current building evacuation performance, clarify the number and location of personnel, comprehensively develop a set of feasible fire emergency plans and regularly drill according to the optimal evacuation plan. They should also invite the local fire department to evaluate the plan and rectify it timeously if necessary. Evacuation routes should be clearly marked on walls and doors on each floor. Emergency exits and emergency exit indication signs should be added, and, to combat low visibility due to smoke, sound signals should be turned on to guide the evacuation [44]. Improving the safety awareness and knowledge of all personnel, broadcasting videos of relevant accidents and safety training for display on screens around the building, and regularly training and evaluating student safety and psychological knowledge, while ranking them, could also be beneficial.

Strengthen safety patrol inspections and eliminate hidden dangers. The comparison of evacuation drill plans found that the number of safety exits has a significant impact on evacuation. Therefore, daily inspections of evacuation staircases and safety exits should be conducted to ensure the smooth flow of emergency evacuation routes. Regularly hiring third-party testing institutions or local fire departments to inspect and evaluate fire-fighting facilities in the building, registering and recording the location of hidden accident facilities, and ensuring that a responsible person makes the necessary rectification within a time limit; hiring a qualified fire protection equipment maintenance company for regular maintenance of fire protection facilities in the building to ensure the functionality of fire protection facilities and improving the completeness of fire safety management are all imperative.

Improve rules and regulations and strengthen institutional constraints. The fire department may carry out strict inventory spot checks periodically on the student apartment buildings in their jurisdiction and take reasonable measures to publicize, notify, rectify, and close down the problems found. The property should be divided into fire zones and responsible persons assigned to monitor each zone. Problems should be reported for rectification or suspension of use. In addition, the relevant rules and regulations should be studied, study meetings held, personnel fire knowledge assessments conducted, etc., to improve the fire control level. Establishing a multi-party linkage mechanism of organizations, including the fire brigade, property management, alarm points, and hospitals, and developing a fire warning and linkage platform under the auspices of big data technology is important, as is ensuring that all parties are connected to resolving and rectifying problems in advance, completing timely rescue operations, and providing feedback results on time to improve the speed and accuracy of action in the whole cycle of accident occurrence, as well as reducing the impact of fire accidents.

(2) Emergency response during the incident

Start the plan in time to evacuate people. After a fire occurs, the property management unit and dormitory management personnel should, according to the severity of the fire incident, launch an emergency plan timeously at an appropriate level, organize a team to extinguish the fire at the initial stage, notify the school security department and fire brigade, and report the fire situation and details of any trapped personnel. Evacuation leading and working groups should be established immediately to evacuate the people from the building. The evacuation leader and the group should maintain communication. If an exit cannot be used, the route shall be immediately reported and re-planned to prevent congestion and serious accidental injuries. If it is impossible to evacuate all of the people, attempts should be made to try to evacuate the floors above the ignition point to two floors below the ignition point to avoid casualties on the high floors. Evacuation of all other personnel should then be initiated according to the fire development situation until all people are accounted for.

Improve self rescue ability and increase chances of rescue. If the evacuation is not completed in a timely manner after an accident, the self rescue ability should be improved, the dormitory doors and windows should be closed in a timely manner, and moist materials should be used to block the gaps to prevent flames from spreading into the interior of the dormitory. When the fire situation decreases or there is an opportunity for evacuation, evacuation should be carried out quickly. No one should advance blindly in the process of escape, and everyone should evacuate according to the horizontal and vertical characteristics of smoke spread, always paying attention to the surrounding environment to cause damage by sudden flame.

(3) Post-incident Summary

Summarize the accident experience and timely feedback and study. The fire department should collect and assess recent accidents, sharing them with relevant units in the area to learn and summarize, especially those resulting in property losses and casualties. All colleges and universities should carefully study and comprehensively consider the occurrence and development of accidents and emergency evacuations, understand the lessons learned, learn from the experience, and compare whether there are problems in their own plans. The property management unit can establish a monthly fire control report to review the current problems checked by the fire department and focus on the fire control of evacuation routes and emergency exits.

Enhance rescue capabilities and enhance overall quality. For fire department and property management, it is necessary to update existing rescue equipment in a timely manner, rectify fire-fighting facilities within each jurisdiction, continuously conduct self drills, maintain a good level of business, and improve rescue capabilities after a fire occurs. At the same time, we will strengthen our publicity and education capabilities within our jurisdiction, utilize new technologies (such as VR) to conduct virtual reality rescue drills and fire prevention education, and improve fire safety from a practical perspective.

5. Conclusions

Taking a multi-story student apartment building in a university as the study object, the characteristics of spreading smoke caused by fire on different floors were simulated, and the safe evacuation performances were compared. The best evacuation drill scheme was optimized, and corresponding fire prevention measures were proposed for future use. The following conclusions were reached:

(1) The visibility due to smoke, ceiling temperature, and smoke layer height at the safe evacuation staircase with ignition on different floors have different effects on the fire-spread characteristics and safe evacuation. Among them, the fire-spread characteristics are significantly affected by the roof structure of the apartment building and the vertical and horizontal diffusion characteristics of smoke. Safe evacuation is less affected by the smoke height; however, it is significantly affected by poor visibility due to smoke and ceiling temperature.

(2) Based on the simulation analysis in this study, it was found that the roof structure of the apartment building and the vertical diffusion characteristics of smoke have a significant impact on the safe evacuation of personnel. The difficulty in safe evacuation becomes exacerbated when the fire position changes from the top to bottom floors and the safe evacuation time increases. The complete safe evacuation times of the top floor following R5-516 ignition and of the middle floor following R3-310 ignition were only 180 s and 210 s, respectively. Safe evacuation could not be completed for the bottom floor following R2-205 ignition.

(3) Based on the established plan for R2-205 ignition, which cannot complete the safe evacuation of all personnel (64 people cannot escape safely within 172 s), the designed evacuation plans 1–4 take 117.3, 104.7, 175, and 147.3 s, respectively, for complete evacuation, with an

improvement in evacuation performance of 31.8%, 39.13%, −0.017%, and 14.36%, respectively. The proportion of personnel evacuation increase is 83.13%, 98.83%, −2.3%, and 38.37%, respectively, indicating that Plan 2 (opening two emergency exits and orderly evacuation) has the best evacuation result.

(4) Further comparative analysis of the significant impact of the number of emergency exits and whether orderly or disorderly evacuation takes place revealed that an increase in the number of exits, regardless of whether the evacuation is orderly or not, can increase the success rate of personnel evacuation by approximately 30% (32.97% and 28.92% in Figure 17). However, if the number of exits is determined, the increase in the personnel evacuation success rate for orderly as opposed to disorderly evacuation is only 10% (15.83% and 10.74% in Figure 17), indicating that the number of emergency exits has a more significant impact on fire evacuation than whether personnel are orderly or not, which can provide important guidance for proposing fire safe evacuation measures under this condition.

(5) Measures and suggestions were proposed to deal with fire from three aspects, namely, pre-prevention, loss reduction in emergency, and experience summary after the event, which is an implementation of the policy of "prevention first and prevention combined". The study results provide important theoretical reference for emergency management and safe evacuation of students following an apartment building fire, as well as providing important guidance for building ecological safety protection and sustainable development.

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Nomenclature

D^*	Characteristic diameter of fire flames, m
Q	Thermal release power of ignition source, kW
α	Growth coefficient, kW/s^2
t	Elapsed time since ignition, s
ρ_∞	Air density, set to 1.2 kg/m^3 in this study
c_P	Air specific heat capacity, set to 1 KJ/(kg·K) in this study
T_∞	Ambient temperature, set to 293 K in this study
g	Gravitational acceleration, set to 9.81 m/s in this study
t_2	Limit of human endurance time
T_2	Air temperature
B_1	Constant, set to 1 in this study

B_2	Constant, set to 0 in this study
R2-205	Room 205 on 2nd floor
R3-310	Room 310 on 3rd floor
R5-516	Room 516 on 5th floor
WCS	West side evacuation staircase
ECS	East side evacuation staircase
Exited (Total)	Total number of safely evacuated personnel
E-W-N	East and west side emergency exits open, and disorderly evacuation
E-W-Y	East and west side emergency exits open, and orderly evacuation
O-W-N	West side emergency exit open only, and disorderly evacuation
O-W-Y	West side emergency exit open only, and orderly evacuation
Stair 1-2 West	WCS from floor 1 to 2
Stair 1-2 East	ECS from floor 1 to 2
Stair 2-3 West	WCS from floor 2 to 3
Stair 2-3 East	ECS from floor 2 to 3
Stair 3-4 West	WCS from floor 3 to 4
Stair 3-4 East	ECS from floor 3 to 4
Stair 4-5 West	WCS from floor 4 to 5
Stair 4-5 East	ECS from floor 4 to 5

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