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Simulation Study on Fire Product Movement Law and Evacuation in a University High-Rise Teaching Building

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Abstract: High-rise teaching buildings are complex public buildings that combine the evacuation risks of school buildings and high-rise buildings. In this regard, studying fire product transport patterns and personnel evacuation characteristics of high-rise school buildings is crucial for safe and rapid evacuation. In this paper, we applied Pyrosim2018 software to build a model of a teaching building and performed numerical fire simulation to analyze temperature, CO gas, and visibility to determine the available evacuation time ASET; meanwhile, we performed evacuation simulation by Pathfinder 2019 to determine the required evacuation time and analyze the congestion problem during evacuation. By improving the evacuation route, secondary simulations were conducted and compared with the previous results. The results show that visibility is the main factor affecting evacuation in of the event of a fire in this school building. Based on the visibility analysis, it is recommended that personnel evacuate from floors four and above within 709.2 S when the fire location is at a specific position on the third floor. While the original safety exits of the school building can avoid a large number of casualties, they cannot guarantee the safe evacuation of all people, and planning a reasonable evacuation route can obviously relieve the evacuation pressure in the high-rise corridor.

Keywords: firefighting; fire smoke; evacuation of people; simulation

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1. Introduction

A teaching facility serves as a densely populated public space where individuals are engaged in teaching, learning, and working activities. Consequently, it becomes imperative to enhance its emergency management and evacuation efficiency in order to safeguard the well-being of both teachers and students [1]. High-rise buildings are complex architectural structures that can accommodate more people than single-story buildings. However, this increases the difficulty of evacuation in the early stages of an emergency, and the issue of evacuation management in such buildings is a global concern [2,3]. In addition, the risks of evacuation in teaching buildings and high-rise buildings are compounded in the context of high-rise teaching buildings. The rapid development of modern society and the economy has led to the emergence of complex high-rise teaching buildings in colleges and universities worldwide. This has heightened the potential hazards associated with evacuation procedures. Therefore, analyzing the evacuation of occupants from high-rise teaching buildings is of paramount importance in campus safety efforts. With the development of the economy, the on-campus facilities of China's colleges and universities have been gradually improved, but the number of students has been increasing year by year, which makes the number of students accommodated in teaching buildings increase with it, and once a fire occurs, the consequences are unimaginable. At present, some colleges and universities are using teaching buildings with aging electric circuits, excessive fire loads, and backward fire protection designs, which have great potential for fire hazards. Therefore, in order to improve the evacuation efficiency of college teaching buildings and reduce the risk of fire, it Is necessary to conduct research on the transport law of fire products and personnel evacuation.

In recent years, many scholars at home and abroad have devoted themselves to the study of fire evacuation and established relevant theoretical models [4–12]. Choi, S. et al. [13] used a social force model to study the interrelationship between the level of evacuation alarm information and evacuation efficiency in high-rise buildings, and Ahmed F., et al. [14,15] analyzed fire scenarios and evacuation plans in large shopping centers, and the results showed that the spread of smoke is related to the building and its internal activities and that corridors and stairs are crucial in the evacuation process. Yang Yuting et al. [16] conducted a numerical simulation of the evacuation of people in a specific fire scenario in a commercial complex and proposed technical measures for fire prevention and control based on the analysis results and the current situation. Wang, H. R. et al. [17] took commercial centers as an example and discussed personnel escape behavior based on parameters such as fire smoke temperature and CO concentration. Liu Chaofeng et al. [18] combined Pyrosim software and Pathfinder software to simulate the evacuation of a high-rise residential building fire and studied the influence of fire smoke dispersion characteristics on safe evacuation under different working conditions. Li, Yan, et al. [19] conducted a study on fire simulation and safe evacuation of a conjoined dormitory building using the fire simulation software Pyrosim and the personnel evacuation software Pathfinder. Zhang, H. et al. [20] used Pyrosim and Pathfinder simulation software to simulate the smoke dispersion and personnel evacuation of a building fire to observe whether all personnel could be evacuated within the safe. The problems in the evacuation process were also analyzed.

In recent years, there has been significant attention given to campus safety evacuation. On one hand, the majority of previous studies have concentrated on examining the factors that influence and the behavioral characteristics of individuals during the evacuation of specific classrooms within teaching buildings. Based on the infrastructure of classrooms, scholars have investigated the influence of factors such as exit locations [21,22], number of exits [23], corridor areas [22], and layouts [24,25] on evacuation time and efficiency. From the perspective of evacuees, scholars have also examined the behavioral characteristics of evacuees during classroom evacuation, including exit selection [26] and path choice [27,28]. On the other hand, only a few studies have broadened their research to consider the transport pattern of fire products and its effect on the evacuation of people. The above studies did not consider the influence of fire products on personnel evacuation during the evacuation process when carrying out numerical simulations of fire spread and personnel evacuation. Therefore, the author selected an atrium-type comprehensive teaching building of a university as the research object and proposed to jointly use the fire dynamics software Pyrosim and the personnel evacuation software Pathfinder and analyze the evacuation process of the personnel by combining with the fire products as the influencing condition. Based on the preceding analysis, this study selected a high-rise teaching building from a university as the actual architectural background. The basic data of the teaching building were measured, the classrooms were observed, and the number of people was counted. A numerical simulation was carried out for the safe evacuation of personnel under the influence of fire products to explore the transportation law of fire products and its influence on the evacuation of personnel, with a view to increasing the demonstration conditions and providing certain guidance for the assessment of the risk of evacuation of personnel in building fires.

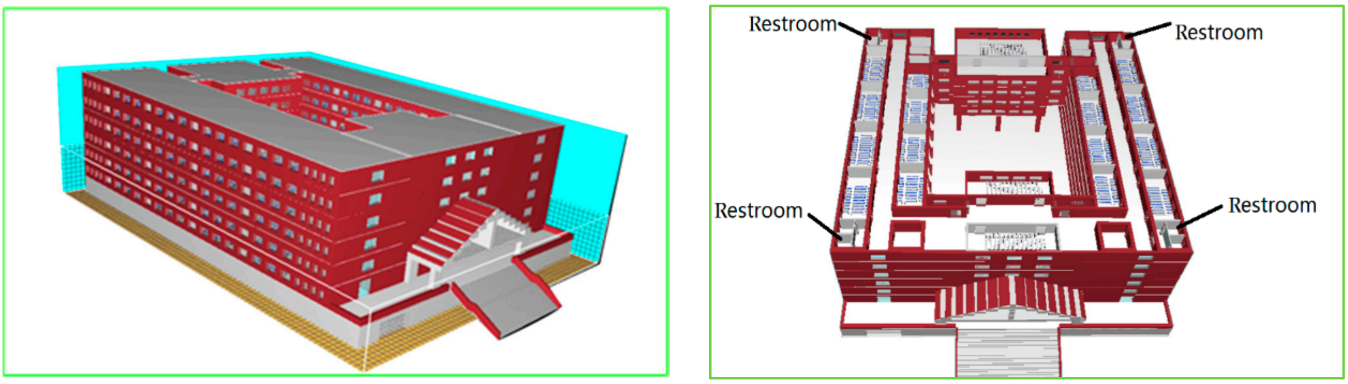
2. Computational Model and Scene Setting

2.1. Software Introduction

Thunderhead Engineering Pyrosim (Pyrosim version number 2018) is a modeling software specially designed for Fire Dynamic Simulation (FDS). Pyrosim2018 is used to simulate and predict the flow of smoke, carbon monoxide, and other toxic gases, fire temperature, and the distribution of smoke concentration in fires.

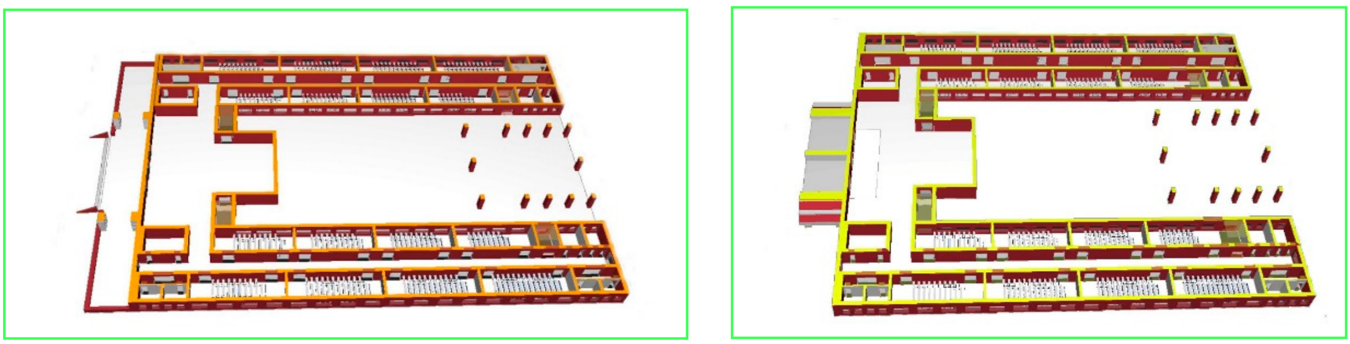
2.2. Simulation Object Introduction

The object of this study is a university teaching building in Hunan Province. The dimensions of the teaching building are 79.9 m × 60.9 m × 21.6 m, from bottom to top, divided into two parts: the garage and the main part. The height of the garage is 3.6 m, and the width of the garage exit is 13 m for vehicles. The height of the main part of the teaching building is 21.6 m, with six floors. Each story is 3.6 m tall. The building has four staircases and two elevators for people to escape. The staircase is 1.5 m wide and has five safety exits. There are 22 offices and classrooms on the first and second floors, respectively, and four bathrooms. These two floors are mainly used for teachers' offices, with fewer personnel, and in case of fire, it is easy to evacuate. The third to sixth floors have the same structure and are mainly used as teaching areas. There are sixteen classrooms, six offices, and four bathrooms on each floor, mainly for students' classes and self-study, which are more densely staffed. The complete model is shown in Figure 1, and the structure of each floor is shown in Figures 2 and 3.



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

Figure 1. Model of the teaching building: (**a**) exterior view of the school building and (**b**) perspective view of the building.



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

Figure 2. Structures of the first and second floors: (**a**) structure of the first floor and (**b**) structure of the second floor.

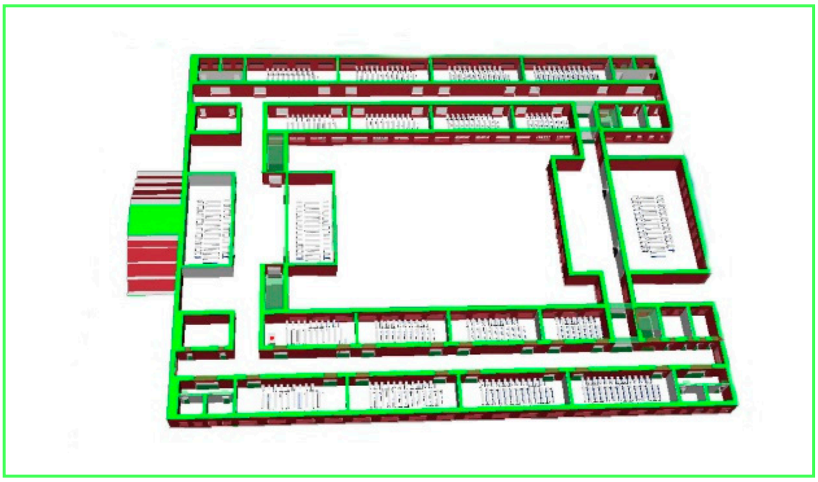


Figure 3. Structure of the third floor (same structure from three to six floors).

As can be seen in Figure 1, it is an atrium building with six floors in the main part. The lowest level of the building is a garage. The restrooms are located in the four corners of the floor, and the rooms with blue desks are classrooms.

As can be seen in Figure 2, the first and second floors of the teaching building have the same internal structure. Each floor has 22 rooms for students' classes and teachers' offices.

As can be seen in Figure 2, the third floor and the sixth floor of the teaching building have the same internal structure. The internal layout of the third floor is slightly different from the structure of the first and second floors. The third to sixth floors are mainly classrooms for students.

2.3. Fire Parameter Setting

According to the literature [28], the maximum fire heat release rate was determined to be 6 MW, and the fire load density was 373.079 MJ/m^2. The fire type was a fast fire, and the fire model was the t^2, with a simulated initial ambient temperature of 20 °C. Based on the most unfavorable conditions, the location of the fire source was determined to be in the first classroom next to the right side of the third floor, i.e., location E in Figure 4, and the area of the fire source was set to 0.25 m^2, assuming that the fire was caused by an electrical short circuit in the classroom that ignited the wooden furniture.

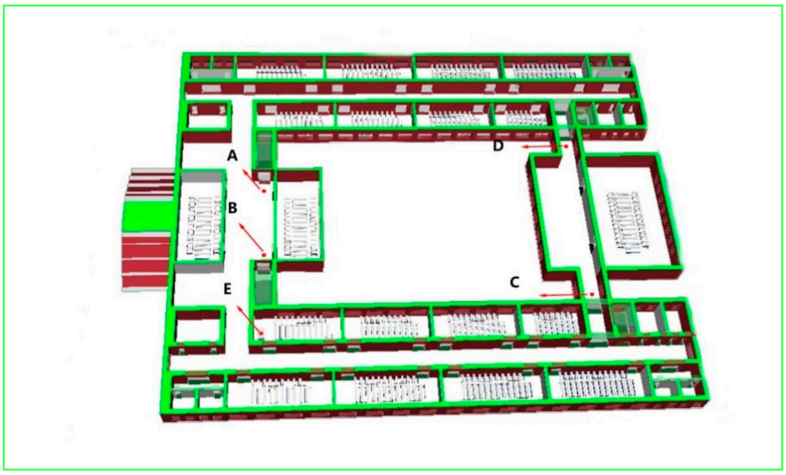


Figure 4. Location of the fire source and measurement point.

The position of four measurement locations on each floor, which are located at the four stairways, is depicted in Figure 4. The measurement points in Figure 4 are equipped with monitoring equipment. Thermocouples and CO detectors were put at 2 m height on each floor at A, B, C, and D. On each floor, smoke detectors were installed at 4 m intervals in the corridor and stairs, 1.8 m from the floor. A temperature slice was installed 1.8 m from the floor on the third level, as well as at the front and rear stairwells, and a visibility slice was placed 1.8 m from the floor on the first floor, as well as at the front and rear stairwells.

3. Analysis of Simulation Results

3.1. Analysis of Temperature Changes

After running the FDS simulation, the temperature distribution of the temperature slicing output of the third floor is obtained, which is shown in Figure 5. According to the literature [29], it is known that the human body can tolerate a temperature below 60 °C for more than 0.5 h, and more than 60 °C will cause discomfort, which makes the tolerance time greatly reduced and is not conducive to safe evacuation. As can be seen from Figure 5, the temperature at B is the most variable among the four measurement points, with the highest temperature around 47 °C, while the temperatures of the other three measurement points are all below 40 °C. This indicates that, except for the fire room, the temperature change in other spaces in the simulation field is not the dominant factor affecting evacuation.

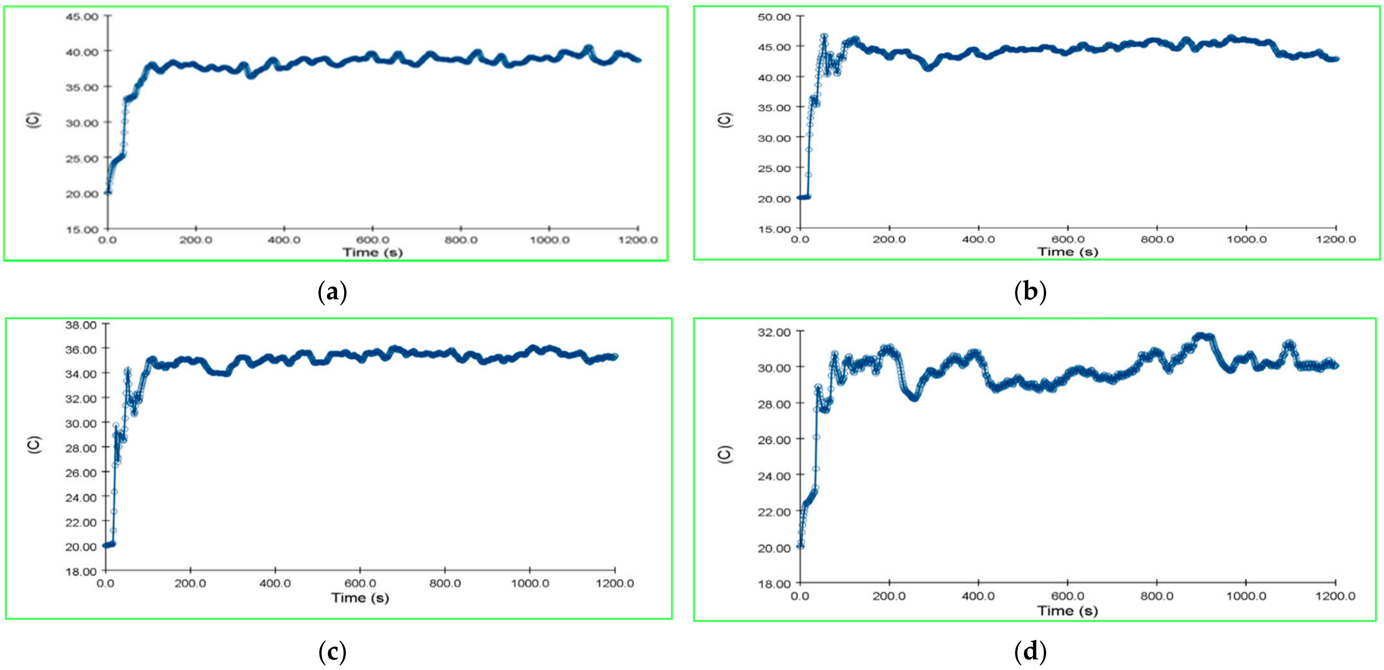


Figure 5. Temperature distributions of four points with time: (**a**) temperature distribution of point A with time; (**b**) temperature distribution of point B with time; (**c**) temperature distribution of point C with time; and (**d**) temperature distribution of point D with time.

3.2. Analysis of CO Concentration

Figure 6 shows the CO concentration at each measurement point. Using 600 ppm as the limit value, each measurement point was studied, and measurement points A, B, C, and D did not reach the limit value, so CO can affect the evacuation of people, but the effect is not significant in this study.

3.3. Visibility Analysis

Visibility generally refers to the furthest distance at which a person can see an object clearly. SP-PE has obtained an acceptable visibility reference value of about 10 m for a person who can just see the safety exit through the experimental data statistics [30]. Visibility slices are shown in Figure 7. When a fire occurs, smoke mainly affects the floor where the source of the fire is located, and visibility in the vertical direction is much faster than the horizontal direction of the decline. The visibility of the upper floors of the fire is affected the most. The visibility of the fire room in the corresponding room on the fourth floor decreases fastest; the visibility of the stairwell is mainly affected above the third floor; and the closer to the fire, the greater the impact of the visibility of the stairwell. As can be seen from Figure 7, the visibility of the corridor outside the room on fire drops to below 10 m at a fire time of 100.8 s. The visibility of the stairwell on the fourth floor drops to below 10 m at 709.2 s. It is recommended that personnel escape from more than four floors within 709.2 s.

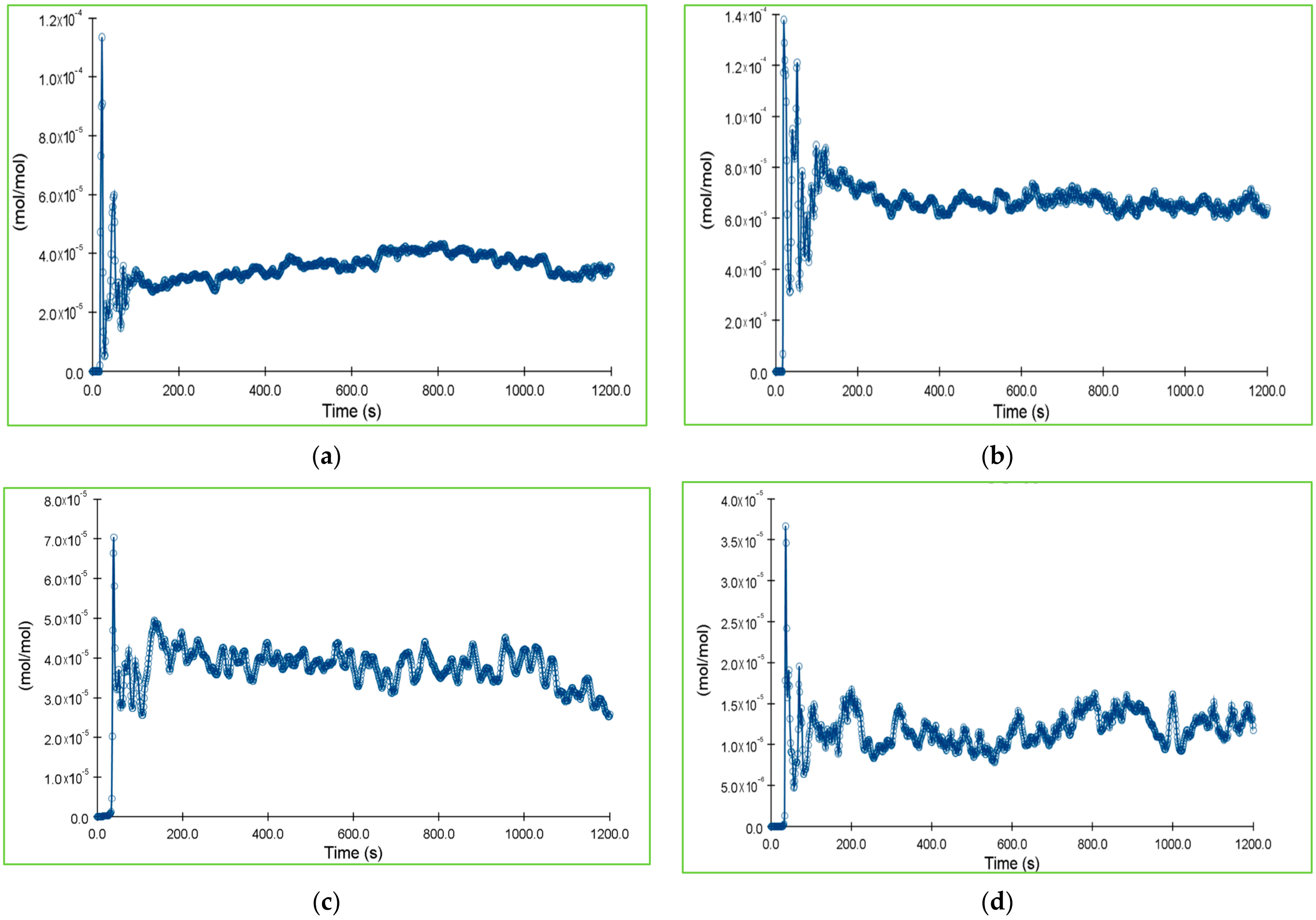
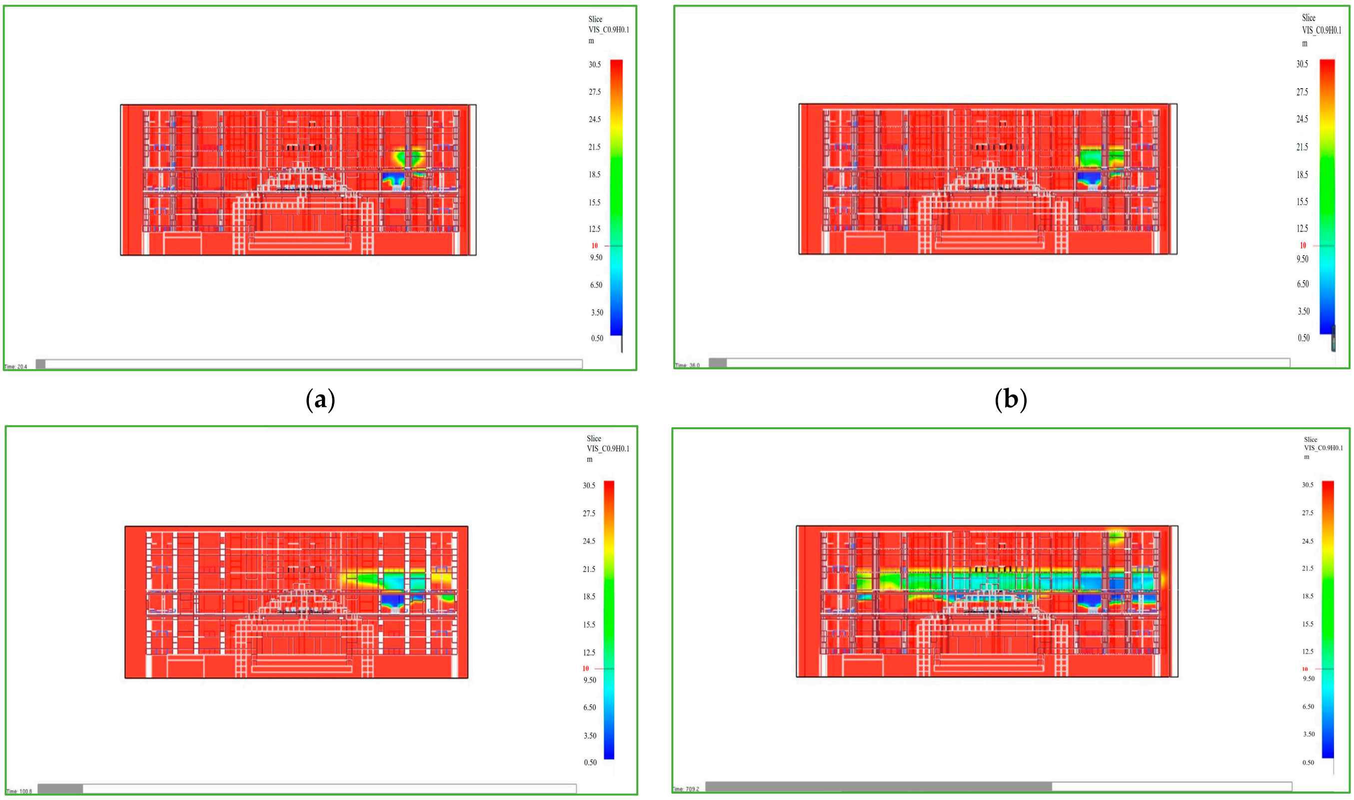


Figure 6. CO concentration variation: (**a**) CO concentration variation of point A; (**b**) CO concentration variation of point B; (**c**) CO concentration variation of point C; and (**d**) CO concentration variation of point D.

It can be seen from Figure 7a that, due to the spread of smoke generated by the fire, the visibility of the fire room fell to less than 10 m in 20.4 s. At this time, the smoke in the fire room was in the high temperature role of upward floating to the room on the upper floors, and at the same time, in the four-floor room on top of the fire room, the visibility also fell to less than 10 m, so in the evacuation process of these two rooms, the personnel needed to evacuate within 20 s.

It can be seen from Figure 7b that, at the time of the fire for 36.0 s, the visibility at the top of the third-floor corridor is extremely low, but in the third-floor corridor, 2 m below the location of the visibility does not affect the personnel escape. At this time, the visibility at the fourth-floor corridor has declined, but the visibility has not yet reached below the threshold, and the visibility of the fire room at the door has been reduced to less than 10 m.

As can be seen from Figure 7c, at the time of fire for 100.8 s, the visibility of the fourth-floor corridor has been reduced to less than 10 m, and the visibility of the fourth floor to the fifth floor of the right side of the stairwell has also been reduced to less than the critical value. At this time, the people who are in the stairwells of the fourth to fifth floors are in a dangerous state and are prone to stampede or congestion. Therefore, within 100 s, people who want to escape from the front stairwells on the fourth to sixth floors need to evacuate as soon as possible; otherwise, they are prone to stampede and other accidents due to insufficient visibility.



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

Figure 7. Changes in visibility: (**a**) visibility slice (20.4 s); (**b**) visibility slice (30.0 s); (**c**) visibility slice (100.8 s); and (**d**) visibility slice (709.2 s).

From Figure 7d, when the fire occurred at 709.2 s, the smoke was covered with the fourth-floor vestibule and the fourth-floor left stairwell, and the visibility of the vestibule was reduced to less than 10 m. It is hard to escape.

From the whole fire process visibility slice, it can be seen that, when a fire occurs, the smoke mainly affects the floor where the fire is located and the floors above. Visibility decreases much faster in the vertical direction than in the horizontal direction. On the floor where the fire started, visibility decreased gradually from the roof to the ground. The main reason for this phenomenon is that the smoke is floated up by the high temperature, and then the smoke particles settle down under the influence of gravity, thus reaching dynamic equilibrium. Therefore, the visibility decreases gradually from top to bottom, and the visibility of the upper floor of the fire floor is affected the most. Visibility is most reduced in the room on the fourth floor, corresponding to the location of the room where the fire started. The visibility of stairwells above the third floor is affected, and the closer the stairwells are to the fire source, the more affected they are.

Combined with the analysis of the variation of each factor, it was found that temperature and carbon monoxide did not have a significant impact on the evacuation of personnel. The evacuation of personnel in this academic building was mainly limited by visibility, among the above factors. The corresponding available safe egress time (ASET) is 709.2 s.

Whether personnel can evacuate safely depends on two characteristic times: one is the time required for the fire to develop to the point where it poses a safety threat to personnel, that is, the Available Safe Evacuation Time (ASET); the other is the time required for personnel to evacuate to a safe area, that is, the Required Safe Evacuation Time (RSET). In order to ensure that personnel can safely evacuate, it is necessary to require RSET < ASET.

4. Analysis of Fire Evacuation

4.1. Model Building

Create a theoretical model based on Pathfinder2019. The artificially set parameters that affect evacuation time in the evacuation model are mainly the settings of safety exit parameters, crowd parameters, and evacuation behavior. For the setting up of safety exits, reference is made to the actual conditions of the teaching building. As shown in Figure 8, there are five safety exits, which contain four double-leaf glass doors with a size of 2.5 m × 2 m and also contain the exit of the main door of the first floor lobby. The door width of each room is 0.9 m, and the staircase width is 1.5 m.

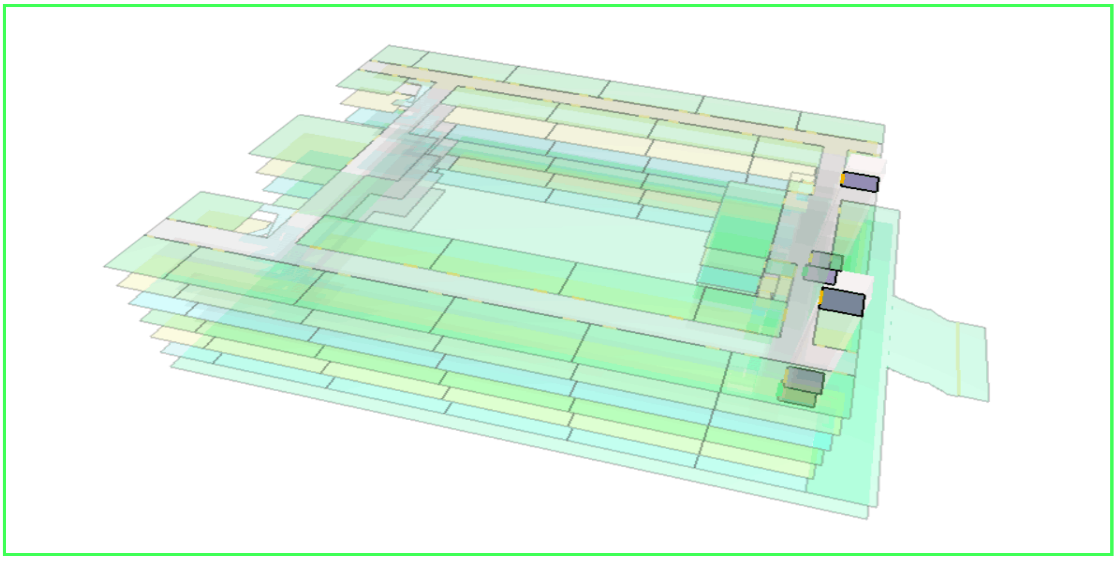


Figure 8. Evacuation model of teaching building.

4.2. Evacuation Scenario Setting

Based on the survey, the types of personnel set in the model are mainly students and teachers, including a small number of security guards and cleaners. According to the survey, the height range of male students is 1.6~1.9 m, and the height range of female students is 1.5~1.75 m; the speed of male students is 1.25 m/s, and the average shoulder width is 45.58 cm, and the speed of female students is 1.23 m/s, and the average shoulder width is 38.85 cm. The number of personnel is based on the maximum capacity of different rooms in the school building, for a total of 1675. Table 1 lists the distribution characteristics of the people on each floor, and the personnel distribution is shown in Figure 9.

Table 1. Statistics of evacuation numbers.

Floor	Number of Persons
1	21
2	22
3	408
4	406
5	409
6	408

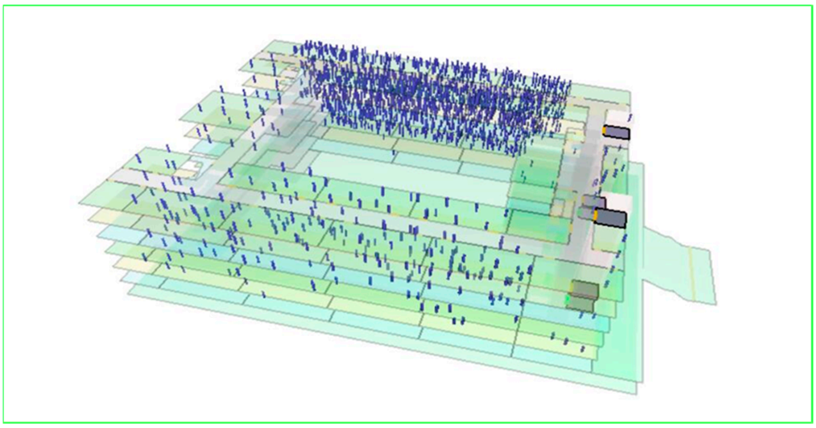


Figure 9. Personnel distribution in the teaching building.

When using Pathfinder2019 to build the model, most of the parameters are defaulted on by the system, and a small part of the parameters need to be set. To better realize the simulation purpose, we constructed the model under the following assumptions:

(1) Personnel movement mode: steering mode;
(2) Evacuation preparation time: 60 s;
(3) Number of personnel: 1675;
(4) Personnel density: 0.5 persons/m^2;
(5) Evacuation speed: male 1.35 m/s; female 1.3 m/s (daily disorder simulation); male 2 m/s; female 2 m/s (disordered and orderly escape);
(6) Safety margin: 0.2.

4.3. Analysis of Simulation Results

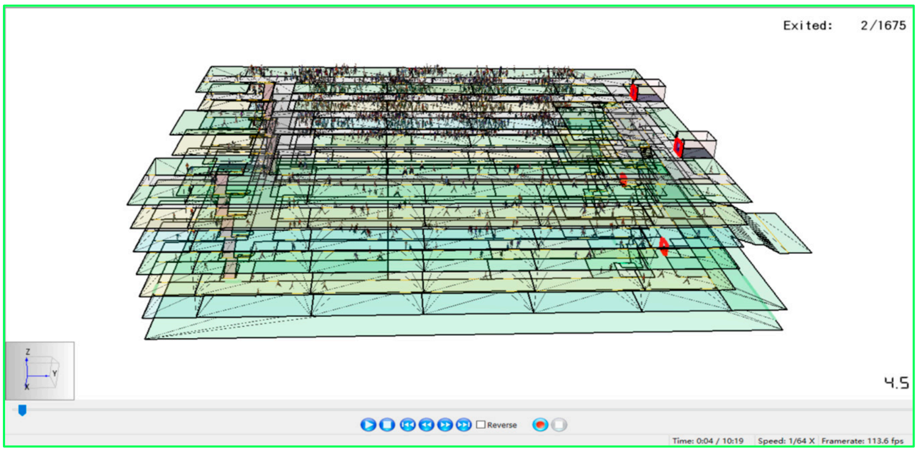
After setting up the above simulation parameters by running the simulation, a disorderly evacuation simulation was conducted, and the evacuation process is shown in Figure 10. From Figure 10, it can be seen that the first person walks towards the exit at 4.5 s. The evacuation of the people in the left and right staircases of the rear building was completed within 200 s, and all the people were evacuated at 619.5 s.

The change in the number of personnel during the evacuation process is shown in Figure 10. The total evacuation time is 619.5 s. About half of the personnel had already escaped at the beginning of the evacuation at 270 s, but the evacuation time of the other half of the personnel exceeded 270 s. This indicates that the evacuation efficiency was gradually decreasing at the later stage of the evacuation.

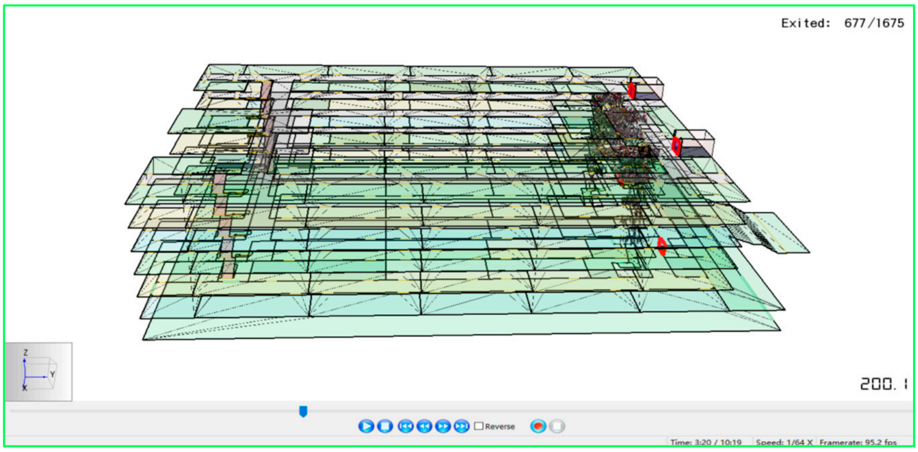
The relationship between the evacuation time and the change in the number of personnel during an unorganized evacuation is shown in Figure 11. From Figure 11, it can be seen that the total evacuation time is 619.5 s. The average evacuation rate of the overall personnel evacuation is slow. Half of the personnel had already escaped when the evacuation started for 270 s, but the evacuation time of the other half was 349.5 s, which was far more than the pre-evacuation time of 270 s, which indicated that the evacuation efficiency was gradually decreasing in the late stage of evacuation.

From Figure 11, it can be seen that all the personnel evacuated at 619.5 s. Considering the evacuation preparation time of 60 s and the safety margin of 0.2, the necessary evacuation time in the disorderly state is $60 + 619.5 \times 1.2 = 803.4$ s. The relationship between the evacuation flow and time for each exit is shown in Figure 12.

From Figure 12, it can be seen that the flow rates at the five safety exits are different. In case of a fire, people should not take the elevator to escape, so they are mostly concentrated in the stairwell. Since the right floor is the classroom where most students attend classes, and the front hallway is narrow, so people are congested in the front stairwell. According to the figure, the right front stairwell safety exit leakage flow is the highest, up to 2.31 people/s, and the left front stairwell safety exit The evacuation flow is followed by 2.1 persons/s at the maximum, and the evacuation flow at the safety exit of the back stairwell is the smallest, 0.5 persons/s and 1.4 persons/s at the maximum of the left and right exits, respectively, which shows that when the personnel evacuate in a disorderly state, the personnel distribution is uneven, resulting in some stairwells being congested while other stairwells are idle, which greatly reduces the evacuation efficiency and increases the evacuation time and the danger of the personnel.



(**a**)



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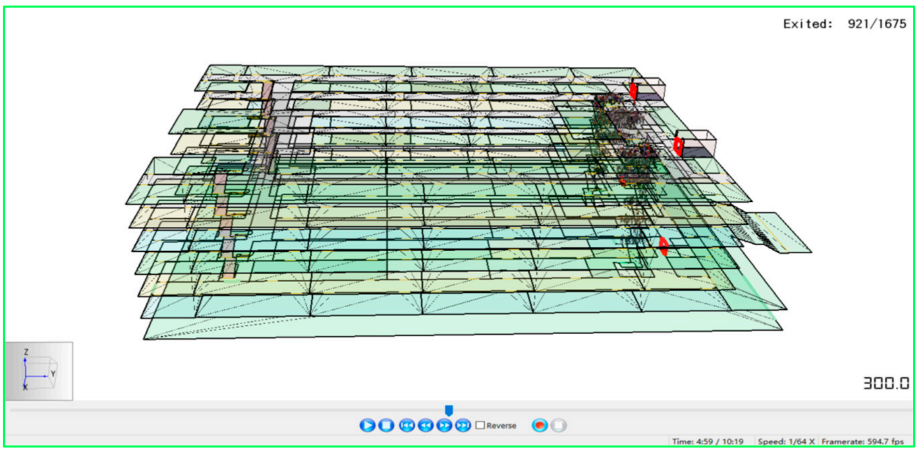
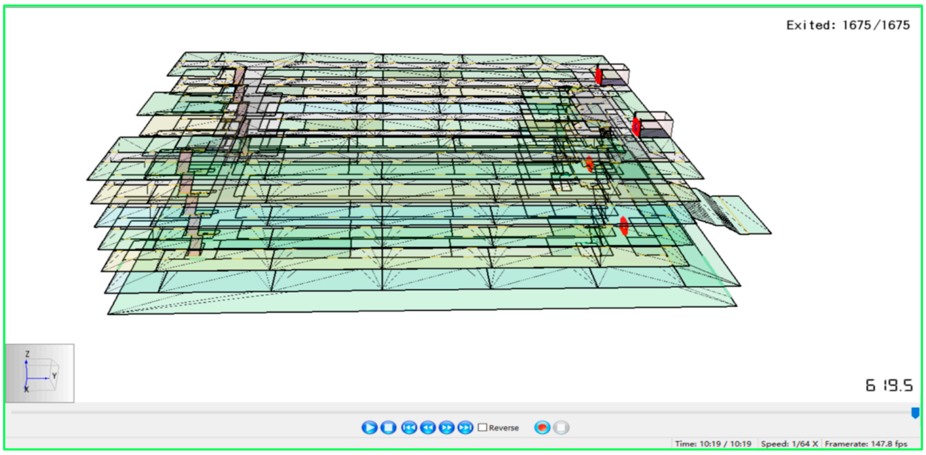


(**c**)

Figure 10. *Cont.*



(**d**)

Figure 10. Distribution of people at different evacuation simulation times (disordered): (**a**) 20.4 s; (**b**) 200.1 s; (**c**) 300 s; and (**d**) 619.5 s.

The simulation in the previous section always defaulted to evacuating people towards the nearest exit, which resulted in a large number of people evacuating towards the staircase nearest to the exit, causing congestion. The personnel behavior is set up in order to further reduce the evacuation time by developing a reasonable evacuation route. According to the arrangement of the teaching building, the evacuation route is set up, and the evacuation route of each floor is shown in Figure 13.

The evacuation routes were set according to the layout of the school building. The relationship between evacuation density and evacuation time for each exit obtained after the second simulation is shown in Figure 14.

From Figure 14, it can be seen that the evacuation density of each exit at this time is not so much different; the evacuation density of each exit in the orderly state is greater than the disorderly evacuation. It indicates that the evacuation of personnel in an orderly state is faster, which is conducive to the escape of personnel.

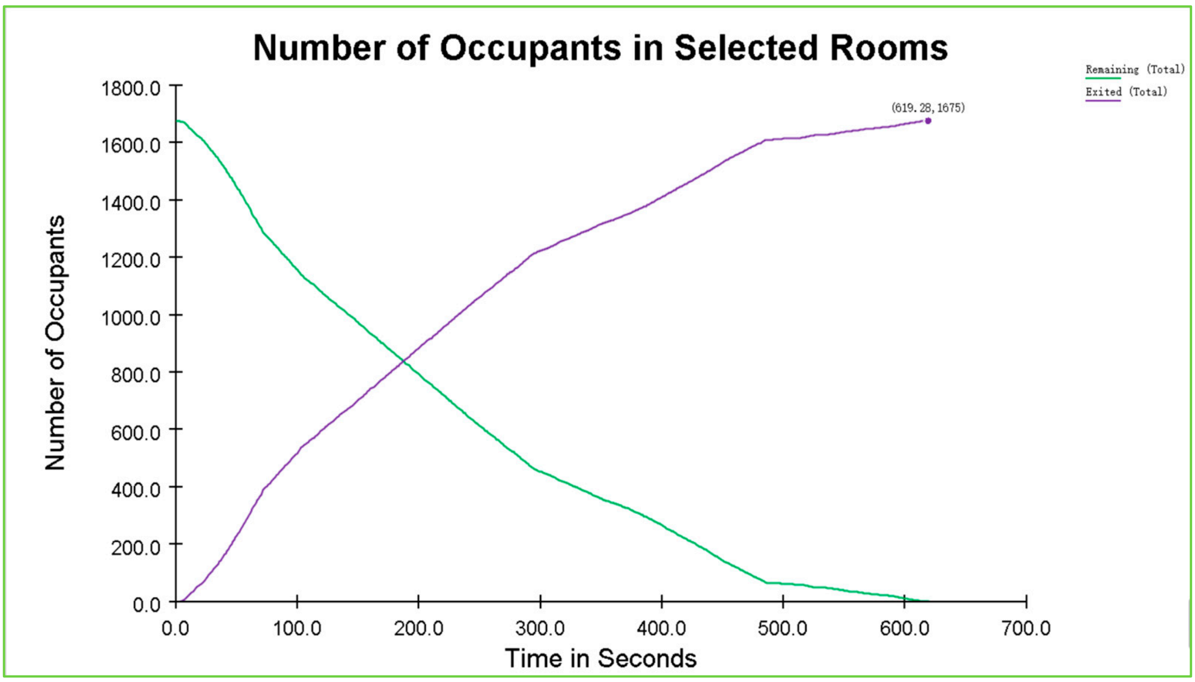


Figure 11. Relationship between evacuation time and the number of evacuees.

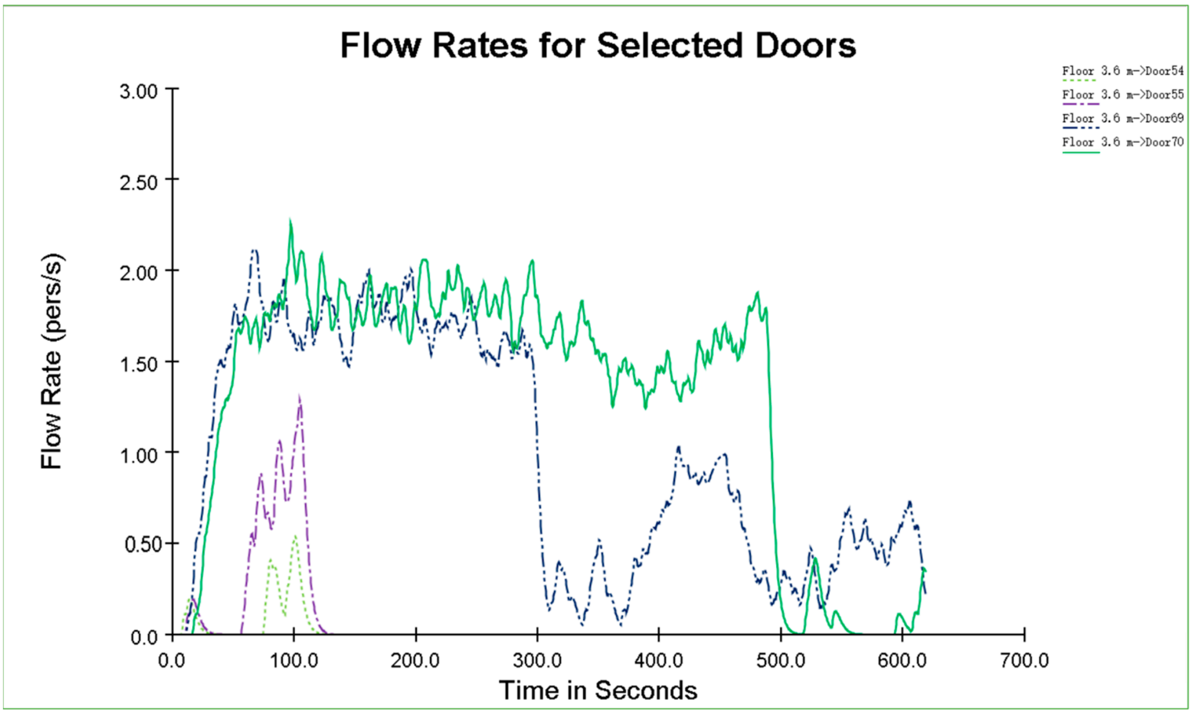


Figure 12. Relationship between flow rates for selected doors and time in cases of disorderly evacuation.

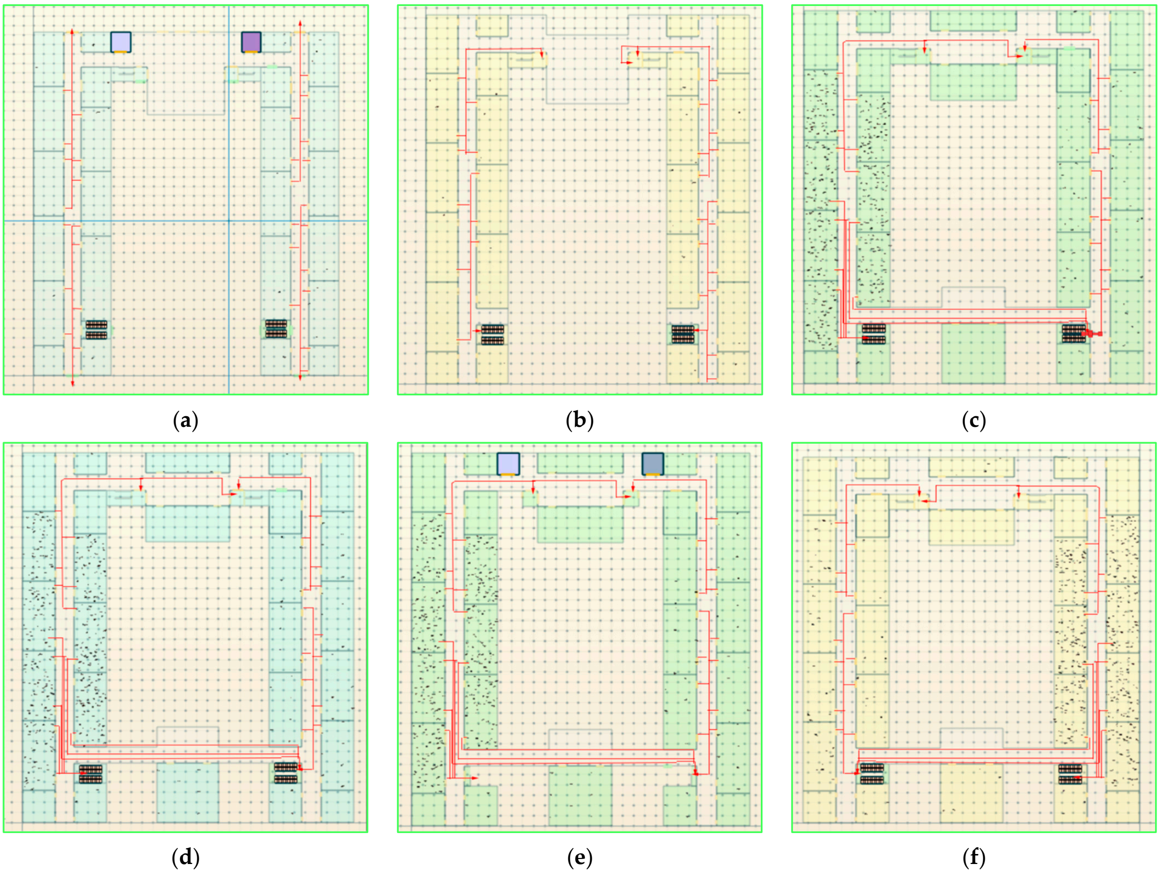


Figure 13. Roadmap for orderly evacuation of each floor: (**a**) first floor; (**b**) second floor; (**c**) third floor; (**d**) fourth floor; (**e**) fifth floor; and (**f**) sixth floor.

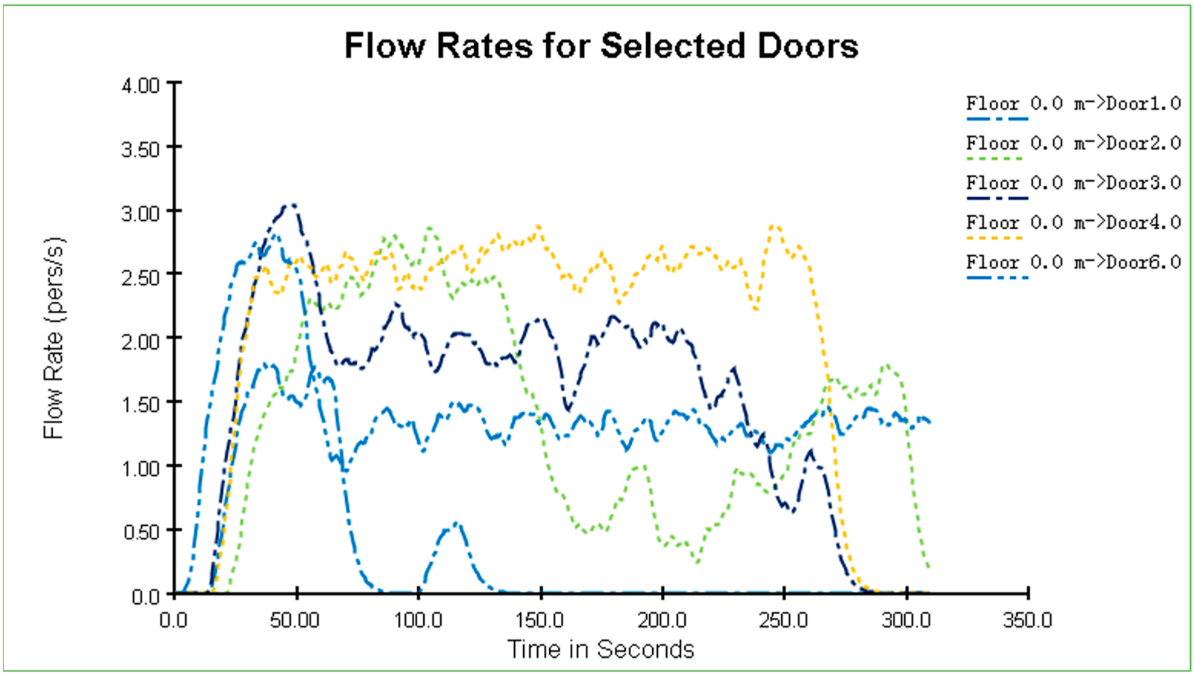


Figure 14. Relationship between flow rates for selected doors and time in case of orderly evacuation.

Comparing the simulation results of orderly evacuation and disordered evacuation, it is found that the time for personnel to leave the floor is much smaller than in disordered evacuation, which shows that orderly evacuation can greatly improve the efficiency of personnel evacuation under fire conditions. Specific data are shown in Table 2.

Table 2. Evacuation time analysis for each floor.

Serial Number	Floor	Disorderly Evacuation	Orderly Evacuation
Time taken for people to leave the floor(s)	6	205.4	73.6
	5	406.2	84.8
	4	429.8	202.0
	3	485.9	230.0
	2	554.5	267.2
	1	619.5	309.8
Total time spent(s)		619.5	309.8

The simulation shows that the evacuation time for the ordered evacuation is 309.8 s. Considering the evacuation preparation time and safety margin, the necessary evacuation time for orderly evacuation is $60 + 309.8 \times 1.2 = 431.76$ s. Since the fire danger time is 709.2 s, the evacuation time for personnel evacuating in disordered evacuation must be 803.4 s, and the personnel cannot escape completely; in the case of orderly evacuation, the necessary evacuation time is 431.76 s, which is much smaller than the fire danger time, so in the case of orderly evacuation, the personnel can be safely evacuated from the teaching building.

Under the Pathfinder2019 simulation environment, the total evacuation time of the disordered model was set to 803.4 s, whereas that of the ordered model was set to 431.76 s. The evacuation time was reduced by 371.64 s, and the evacuation efficiency was increased by 46.2%. Evidently, the orderly evacuation was beneficial to reducing the overall evacuation time in the present case.

5. Conclusions

In this paper, the software Pyrosim 2018 and Pathfinder 2019 were used to simulate the transport law of fire products and the evacuation of personnel in a college teaching building, and the main findings are as follows:

(1) In the college building fire simulation, temperature and CO gas can cause direct injury to personnel, but they are not the main factors affecting evacuation. Visibility is the main factor affecting evacuation, which can lead to slower evacuation and has the greatest impact on ASET. This shows the importance of emergency evacuation lighting in teaching buildings.

(2) Setting reasonable evacuation routes can effectively reduce evacuation time, so the emergency plan should be sound and regular emergency evacuation drills should be conducted to achieve the goal of preventing accidents and reducing the consequences of accidents.

(3) The conclusion of this study is only applicable under the assumption of its validity. As the development trends of incidents are influenced by a combination of discussed objective and subjective factors, external environmental factors such as weather and wind direction also impact the spread of fire, the dispersion patterns of fire byproducts, and the difficulty of evacuation. Therefore, incorporating research into the effects of various environmental factors in future studies can further mitigate the severity of post-incident consequences.

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