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A Case Study on the Evacuation of People during a Fire in the Workshop of a Large Factory

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Abstract: A workshop, as a crowded place, is quite easy to cause serious casualties and economic losses once there is a fire. In this paper, Pathfinder software was used to simulate fire emergency evacuation in a workshop of a large factory with building structural symmetry. According to the simulation results, several obstacles to the evacuation were discovered and further analyzed. The results showed that the main factors affecting the evacuation were the width of exits, the distribution of occupants and the effective evacuation width of stairs. Among them, only changing the width of exits had little influence on shortening evacuation time. While changing the effective evacuation width of stairs could greatly relieve the evacuation pressure, every increase of 0.5 m in the width of the staircase could shorten the evacuation time by 30.0 s. Meanwhile, the larger the number of people in high-rise buildings, the longer the evacuation time was. Therefore, the means of restricting people from entering the high-rise buildings in batches could be used to prevent personnel from being evacuated in time when a fire incident occurs.

Keywords: Pathfinder; factory; simulation; fire emergency evacuation; safety engineering

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1. Introduction

Emergency evacuation is very important in the event of a fire in any type of building or where large numbers of people are expected. As one of the world's largest industrial countries, China has mushroomed into all kinds of labor-intensive industries, prompting the existence of many large workshops. There are a large number of occupants and a high density of workshops. In the event of an emergency such as a fire, it is highly likely to result in mass casualties and large economic losses. In the case of sudden accidents such as a fire, it is quite easy to cause mass deaths and injuries, and it would also cause relatively large economic losses. For instance, there were two massive explosions in quick succession at the port of Tianjin in China in 2015. Six large fires and dozens of small fires occurred, causing heavy casualties and property losses [1]. Therefore, issues of how to ensure the safety of occupants in emergency evacuation, effectively improve the conditions of emergency evacuation, and avoid casualties have become primary points of concern in the current workshop management research.

At present, scholars all over the world have conducted a lot of research on the evacuation in different conditions with different methods. There were several influences on people's evacuation efficiency. As for the evacuation behaviors, people's degree of fatigue could have an impact on the evacuation time. Ronchi et al. [2] proposed and simulated the conceptual model about the influence of fatigue on stair evacuation and pedestrian movement to describe human behavior in emergency evacuation more accurately, then presented a more comprehensive conceptual model for representing the impact of fatigue on evacuee performance during building staircase evacuation. The model is presented, taking into account its conceptual development and the issues related to its implementation. Helbing et al. [3] studied the behavioral characteristics of crowds in large public spaces, discussed the behavioral performance of people in a panic state, and proposed that the orientation setting of walls in buildings was related to evacuation efficiency. Although the role of people's information sharing is also greatly neglected under panic, Deng et al. [4] conducted an emergency evacuation simulation based on the information sharing mechanism to explore the impact of information sharing-related factors on indoor emergency evacuation. However, the simulation results show that evacuation navigation can be improved even if evacuees' information sharing is incomplete, and the overall evacuation performance of evacuees can also be improved. Jin et al. [5] argue that over-diversified targeting strategies clearly waste traffic capacity and delay the evacuation process. Therefore, global evacuation time and local density need to be balanced in the crowd evacuation process. Frank et al. [6] proposed that adding physical intervention facilities before the exit could improve traffic efficiency and safety. Kong et al. [7] introduced that the indexes of evacuation safety, including the number of cluster people at exits and staircases, the duration of detention, and the time required to complete evacuation could reduce evacuation time. Li et al. [8] designed a fire evacuation model based on the dynamic coupling of the Fire Dynamics Simulator (FDS) and cellular automata (CA), then analyzed crowd behavior during evacuation using computer simulation based on multi-agent technology. Ronchi et al. [9] presented that the evacuation areas should be reasonably divided into workshops, while external staircases and safety exits should be added to the upper floors of the workshop. In addition, safety management should be strengthened through the analysis of evacuations in a workshop. Kekki [10] pointed out that most of the fires are caused by human activities. The human behavior and people's performance in the fire are discussed. The results show that the irrational mentality people had in fire accidents, such as recurrent actions, koinotropy and phototaxis, would cause serious injuries. Kinsey et al. [11] explored the modeling of evacuation behavior and cognitive bias in building fire safety design and evacuation procedures, suggesting that such assessments and action choices can be made using either automated or reflective processing systems depending on the nature of the situation and the experience of the individuals involved. Da et al. [12] made a preliminary attempt to construct an indoor fire emergency evacuation knowledge graph and proposed a quaternary knowledge representation model. It is complemented by effective applications in the field of fire emergency response.

On the other hand, factors and parameters, such as CO concentration, temperature and visibility conditions, in the buildings could also influence the evacuation of people. According to the previous studies, the presence of smoke may not only have a physiological impact on the evacuees but may also lead occupants to adapt their evacuation strategy through the adoption of another exit, and the decline in visibility could cause a decrease in evacuation speed, resulting in a longer evacuation time. When the visibility was not lower than 10 m, it had little effect on the evacuation [13]. Xiao et al. [14] analyzed the changing patterns of smoke visibility, carbon monoxide concentration and ambient temperature at a prefabricated building construction site to determine the available safe evacuation time. In addition, the time required for safe evacuation and the factors affecting the evacuation time were determined by simulation using Pathfinder software in conjunction with the physical attributes of the personnel, the evacuation speed and the personnel ratio. Cui et al. [15] studied the influence of temperature and CO concentration on people's evacuation and improved the model proposed by Östman et al. [16] by modifying it to the time limit of endurance for a normally dressed person in a high-temperature environment. Gwynne et al. [17] introduced a kind of adaptive behavior in the evacuation model, making inhabitants able to choose the most feasible evacuation exit in the fire. In this paper, these models will be referred to when setting the Available Safety Egress Time (ASET).

In general, the analysis of evacuation is well established in all countries of the world. Most of these studies come from the field of engineering (29%), followed by architecture and building technology (19%), computer science (13%), physics (11%) and thermodynamics (10%). Some studies came from transportation and other different fields [18]. Even in articles focusing on workshop evacuation, it could be observed that different influencing factors have not been analyzed deeply and comprehensively. Hence, this paper takes a large-scale workshop as the research object, establishes an evacuation model based on Pathfinder simulation software, and studies the impact factors of evacuation under sudden fire so as to provide a basis for the selection of the safety structure of similar buildings.

2. Model Construction

2.1. Software Introduction

At present, there are many kinds of simulation software such as SIMULEX, STEPS, Building EXODUS, and FDS + Evac. The specific scope of application is as listed in Table 1 [19–22].

Table 1. The list of application scope about various simulation softwares.

Simulation Software	Scope of Application
FDS + Evac	Sports stadiums, shopping malls and other public places; ships, trains and other large vehicles.
Building EXODUS	Supermarkets, hospitals, stations, schools and other large space building.
Pathfinder	Suitable for evacuation simulation on large buildings.
SIMULEX	Suitable for the large buildings which have complex geometry such as multiple floors and staircases.
STEPS	Suitable for the various buildings and trains with predetermined movement tracks.

Pathfinder is an intuitive and easy-to-use intelligent emergency evacuation assessment system developed by Thunderhead Engineering. The simulation system could build a model according to the actual size of the building, carry out a graphical virtual drill for each individual movement in multiple groups, and perform a visualization output of the simulation results at the same time [12]. Pathfinder's motion environment is a three-dimensional triangular grid designed to match the actual dimensions of the building model. This moving grid can be entered manually or automatically based on the imported data. (FDS geometry). In all simulations, doors provide a mechanism to connect rooms and track the flow of occupants, and depending on the specific choice of simulation options, doors can also be used to explicitly control the flow of occupants. Stairs are also represented by special navigational mesh edges and triangles. On the motion grid, the occupants are modeled as upright cylinders and travel using an agent-based technique called reverse direction. Each occupant computes the move independently and can be provided with a unique set of parameters (maximum speed, exit selection, 3D model, etc.) [23].

In the specific parameter setting, the Pathfinder software consists of two modes of occupant movement: Society of Fire Protection Engineers (SFPE) mode and Steering mode [24]. In SFPE mode, the main criterion for pedestrians to choose a path is the path length, and the movement rate is determined by the density of the crowd in the room. At the same time, pedestrians select the evacuation exit according to the nearby principle, while the door restricts the flow of occupants. Steering mode is controlled by the integrated action of path planning, guiding mechanisms and collision handling. During the process of evacuation, the route is confirmed according to the path and occupant distance. If the distance between people or the path of the nearest point exceeds a certain threshold, new paths could be regenerated to accommodate new forms [25–27]. In this mode, people use the steering system to move and interact with others. This model attempts to mimic human behavior and movement as much as possible. People accomplish objectives independently while avoiding other people and obstacles. The flow rate of the gate is not specified but is the result of interactions between people and between boundaries. In addition, people prefer the closest exit for evacuation in many real-life cases. Considering that the Steering mode could present a more realistic situation, it was chosen for the simulation of people's evacuation in this work.

According to the complex functional areas and personnel distribution of the building, Pathfinder software was used to build an accurate structural model of the workshop. Under the maximum speed, exit selection and detailed parameter setting of the 3D model, the most realistic and nearest evacuation path is simulated through the steering mode. The evacuation results obtained by this method are credible.

2.2. Scenario Introduction

2.2.1. Pathfinder Modeling

In this paper, a large assembly workshop was used as the research object, which covered an area of 1500 m^2, and the building area was 2160 m^2. There were three floors in the workshop, where the first floor also covered an area of 1500 m^2, while the second and third floors had the same area of 330 m^2. The specific statistical data of the workshop are as shown in Table 2, while the plant of the first floor in the workshop is shown in Figure 1a, and the corresponding 3D spatial model is presented in Figure 1b. The main area was equipped with apparatus, which was 8 m long and 2.4 m wide, including 12 sets of equipment being distributed symmetrically. The first floor of the workshop mainly included 5 exits, of which the width of the exits distributed to the small public rest area and the production area was 2 m, and the width of the rest exits was 3 m. Two stairs with a width of 2.5 m were distributed on both sides of the second and third floors, so the effective evacuation width was 5 m, as indicated in Figure 1c. In order to simplify the simulation processing, the stair specifications were the same in this paper. Moreover, the transition platform was set at 2.5 m and 7.5 m high in the space. The effective evacuation width of the transition platform was 10 m.

Table 2. The list of the workshop parameters.

Parameters	Statistical Data		
The covering area of workshop (m^2)	1500		
The building area of workshop (m^2)	2160		
The building area of floor (m^2)	F1 #	F2 #	F3 #
	1500	330	330
The width of exits (m)	2 or 3		
The width of staircase (m)	2.5		

#: F presents the word "floor".

2.2.2. Occupants Parameter Setting

The age and gender of occupants and the response to emergencies have a great impact on evacuation. In consideration of the particularity of the gender and age ratio of workshop occupants, evacuees were divided into 2 categories by referring to the national standard of China "Human Dimensions of Chinese Adults" [28], which were listed in Table 3.

2.2.3. Occupants Parameter Setting

The total number of occupants in the workshop was fixed, but it varied with different periods. The first floor served as the main production line, with about 800 people during the working hours, of which about 600 were in the production area. The number of people in the office area on the third floor was almost unchanging, generally around 200. Since the workshop operated a system of two shifts, with about 800 occupants in each shift, the number of occupants in the workshop reached its peak value at the time of shift changing, when the capacity on the second floor reached its saturation. The number of occupants in the whole workshop would reach about 1500.

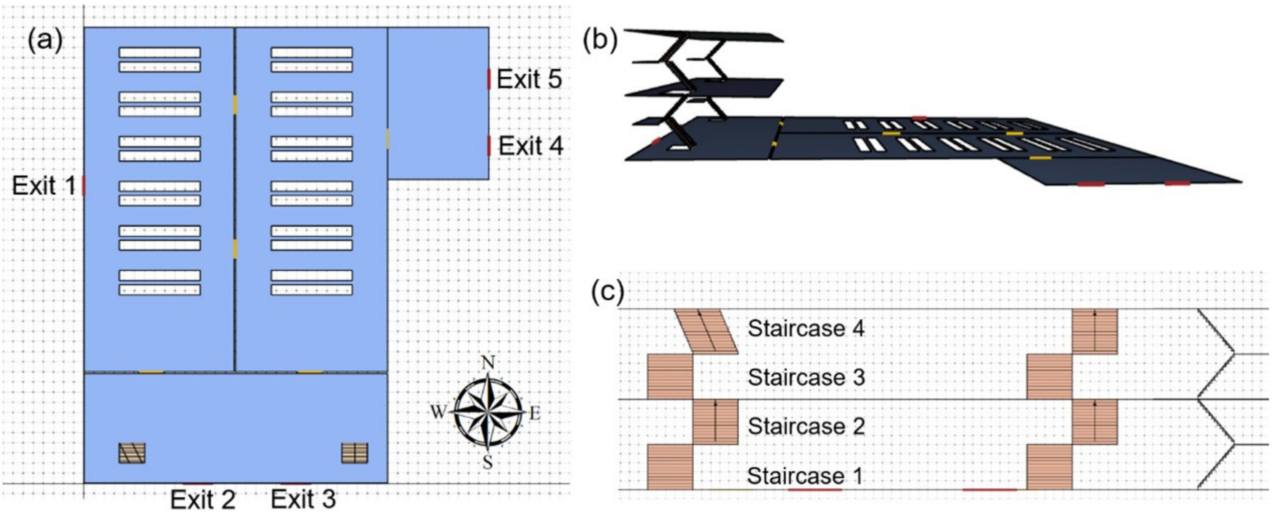

Figure 1. Schematic diagrams of the workshop for (**a**) top view of the first floor, and (**b**) 3D view and (**c**) front view and left view of the staircases.

Table 3. The list of the set occupants' parameters.

Parameters	Occupant Types	
	Young Men	**Young Women**
Evacuation speed (m/s)	1.51	1.45
Shoulder width (m)	0.41	0.38
Proportion (%)	5.5	94.5

According to the actual situation and data query, the number of occupants in the workshop was set to fit the rush hour and the daily working hour, respectively. During the daily working hours, the second floor was almost in the state of "no-load". The specific numbers of occupants were set in Table 4.

Table 4. The list of the specific number of occupants.

The Layer Number	First Floor	Second Floor	Third Floor
Number of occupants in rush hour	800	600	100
Number of occupants in daily working hour	800	50	200

3. Emergency Evacuation Analysis of Workshop Fire

The concept of safe evacuation in a building fire refers to the action of evacuating all the people in the building safely to a safe area before the fire smoke triggers casualties. Whether people could be evacuated to a safe area or not depends on two characteristics. One is the time before a fire developed into a danger to humans, which could also be called ASET. Another is the Required Safety Egress Time (RSET), which means the shortest time for evacuating people to a safe area. If all the occupants could be evacuated to a safe area before the fire reaches a dangerous state, namely RSET < ASET, then the fire safety design of the building is considered safe [29].

3.1. Available Evacuation Time

The available evacuation time (which has the same definition as ASET) is mainly determined by the structure of the building and the equipment. Therefore, generally, ASET is fixed. The time is determined by the height change of the smoke layer, the temperature above and below the smoke layer, the concentration of CO in the air, the visibility and other relevant parameters when the fire occurs. Moreover, ASET is also determined by the fire and combustion characteristics, reflecting corresponding parameters such as heat release rate (HRR), smoke production, and so on. The critical conditions in danger of fire are usually determined according to the following situations [30–32].

1. The temperature of the smoke at the 2 m height of all the exits should be no more than 50 °C.
2. The visibility at the 2 m height of all the exits should be larger than 10 m.
3. The concentration of CO at the 2 m height of all the exits should not exceed 500 ppm.

Obviously, people would be dangerous as long as the fire grows beyond the limits specified in any of the above conditions. Based on the fire scenario in this paper, a PyroSim model of the core area was built, and the simulating computation has been conducted. The source of ignition was set as polyurethane (PU) material. According to the relevant technical regulations for smoke control and extraction in China, the fire power was set at 4.5 MW, and the fire growth pattern was t^2. The model was as shown in Figure 2a. The emergency condition that the mechanical smoke exhaust in the factory was invalid and only natural smoke extraction worked by using the openings of doors and windows was chosen as the situation for modeling. Monitored points for visibility, CO concentration and temperature were settled on each door, and the corresponding data are shown in Figure 2 as well.

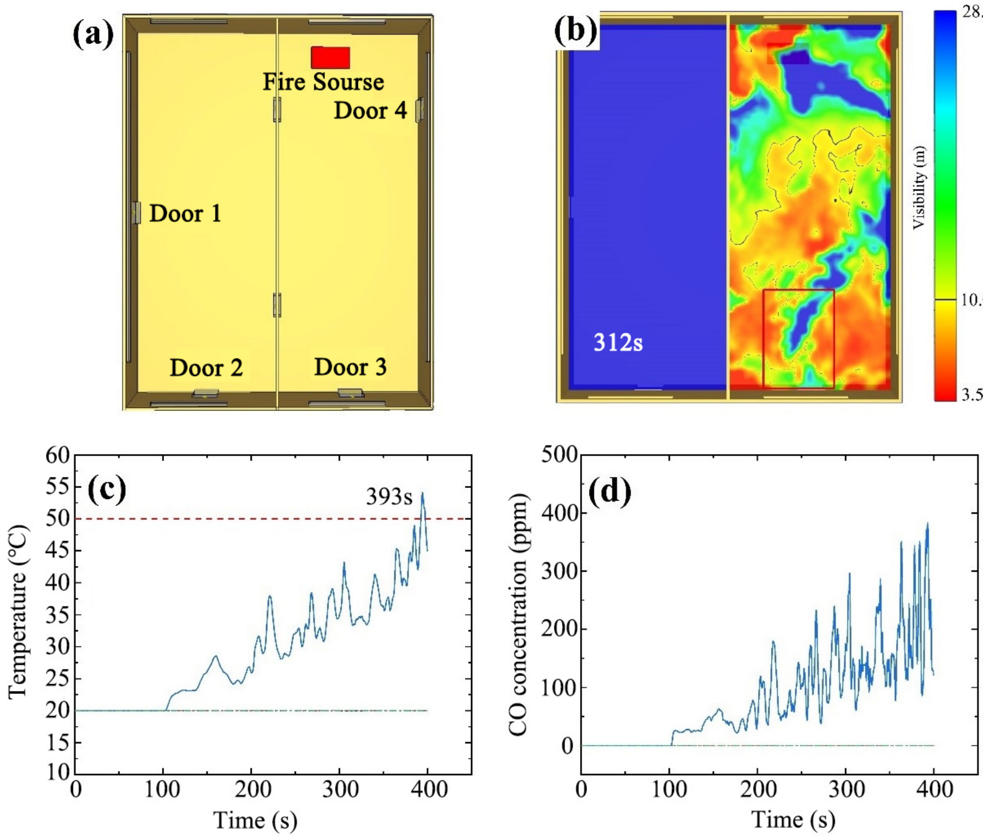

Figure 2. PyroSim model about (**a**) core area of the first floor for the workshop, simulated results of (**b**) visibility, (**c**) temperature and (**d**) CO concentration at 2 m height of Door 3.

From the above figure panels, the visibility indicator reached the critical damage threshold around Door 3 in the whole calculation processing. Meanwhile, from the center to Door 3, the visibility in the path could be lower than 10 m, influencing people's evacuation to some extent. The temperature indicator reached the critical limit at 393 s, while the CO concentration did not exceed 500 ppm in the whole 400 s calculation time. Therefore, 312 s was chosen as the ASET in this paper. In addition, based on the previous research [15,16], and considering the influence of air humidity and that the shortest route in evacuation may contain several walkways, the average smoke flow temperature in these paths can be used to calculate the ultimate endurance time. The ability to endure the hazard factors changes to one-third in the same concentration at a static condition. Thus, the time limit of endurance for people in the setting temperature and CO concentration environment could be calculated by using the following Equations (1)–(4):

$$\overline{T}_E = \int_0^t T_E dt/t \tag{1}$$

$$\overline{C}_{CO} = \int_0^t C_{CO} dt/t \tag{2}$$

$$t = \frac{3.28 \times 10^8}{\overline{T}_E^{3.61}} \tag{3}$$

$$C_{CO} = 36960.5/\overline{C}_{CO} \tag{4}$$

where

$\overline{T}_E$ is the average temperature at the time t;
T_E is the real-time temperature at a certain exit;
t is the time limit of endurance;
$\overline{C}_{CO}$ is the average CO concentration at the time t;
C_{CO} is the real-time CO concentration at a certain exit.

On the basis of the selected temperature and CO concentration values in this study, when the temperature reached 50 °C and the CO concentration reached 500 ppm, the time limits of endurance were 241 s and 74 s, respectively. Thus, even approaching the critical thresholds, there was still some time remaining for people's evacuation. Therefore, it was practical to choose a temperature of 50 °C, a CO concentration of 500 ppm and visibility of 10 m as the critical thresholds, and there were some safety margins for these values.

3.2. Safe Evacuation Time

The safe evacuation time (which has the same definition as RSET) is mainly composed of three parts, which are T_1, T_2 and T_3, respectively. T_1 is fire detection and alarm time, which means the time from the fire occurring to when people in the room perceive the fire. T_2 is the time used for evacuation preparation-response time. T_3 is the time applied for evacuation to the safe zone-evacuation movement time. Considering the safety margins, the required evacuation time is RSET = $T_1 + T_2 + T_3$.

T_1 usually depends on an automatic or manual detection system, including controls of the central panel and others. However, there is a certain difference in response time for different types of buildings, which is related to the adoption of fire alarm systems in interior buildings. Meanwhile, it is affected by subjective factors [33].

Based on the stipulation in the relative Chinese standard "Fire Alarm Control Unites" [34], at present, the smoke detector used in engineering could detect the fire with a radiation power of around 100 kW and then activate the alarm system. It could not exceed 10 s from when receiving the fire alarm signal to the alarm time. According to the fire growth regularity in this paper, the fire power would exceed 100 kW at 46.2 s. Therefore, 60 s was chosen as T_1 under comprehensive consideration.

In a previous study, the response time of people's evacuation inside the aircraft cabin was set at 2 s [16], while the scenario in this study was larger than the aircraft cabin, and it was easy to be realized if fire occurred with such a population intension level. For conservative consideration, T_2 was set to 60 s in this paper. Considering a 1.1-times safety margin, the evacuation movement time T_3 should be less than 174.5 s.

4. Simulation on Occupant Evacuation

4.1. The Rush Hour

The number of occupants in the workshop would reach its maximum during shifts. At this time, there were 800 people on the first floor, 600 on the second floor and 100 on the third floor, respectively. The width of the stairs and the exits were set at 2.5 m and 3 m, respectively.

According to the simulation results, the evacuation time in this scenario was 200.0 s, higher than 174.5 s. As shown in Figure 3a, by observing the evacuation processing of each floor, it could be found that the congestion on both sides of the stairs was the most obvious on the second floor because it was serving as a critical junction for personnel flow and the number of people reached saturation. As shown in Figure 3b, there were most people on the first floor, but the building area was also the largest and there were many choices of exits, so the congestion was not obvious, taking the evacuation density at the 10s as an example. The occupants on the first floor were evacuated completely at 54.9 s.

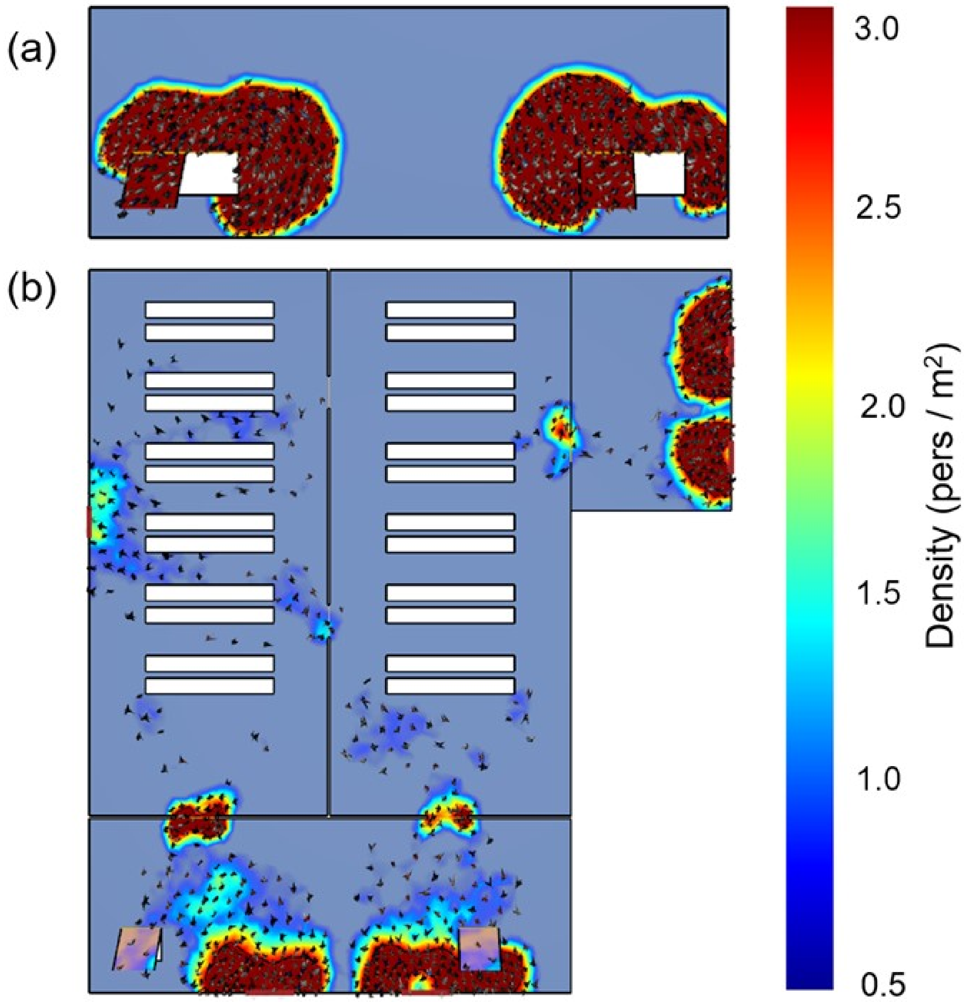

Figure 3. Simulation diagrams of people density during evacuation on (**a**) the second floor, (**b**) the first floor at 10 s of evacuation.

An analysis of the utilization rate of the five exits separately is shown in Figure 4a: Three exits numbered 1, 4, and 5 were mainly used for evacuating the original occupants on the first floor. Therefore, at 54.7 s, the flow rate would reach 1 pers/s, and then it "failed", which was consistent with the simulation process. In the whole evacuation processing, the exit that assumed the main evacuation function was the south exit, and the flow rate was maintained at 1.96 pers/s after 74.0 s. Hence, the width of the south exit played an important role during the evacuation.

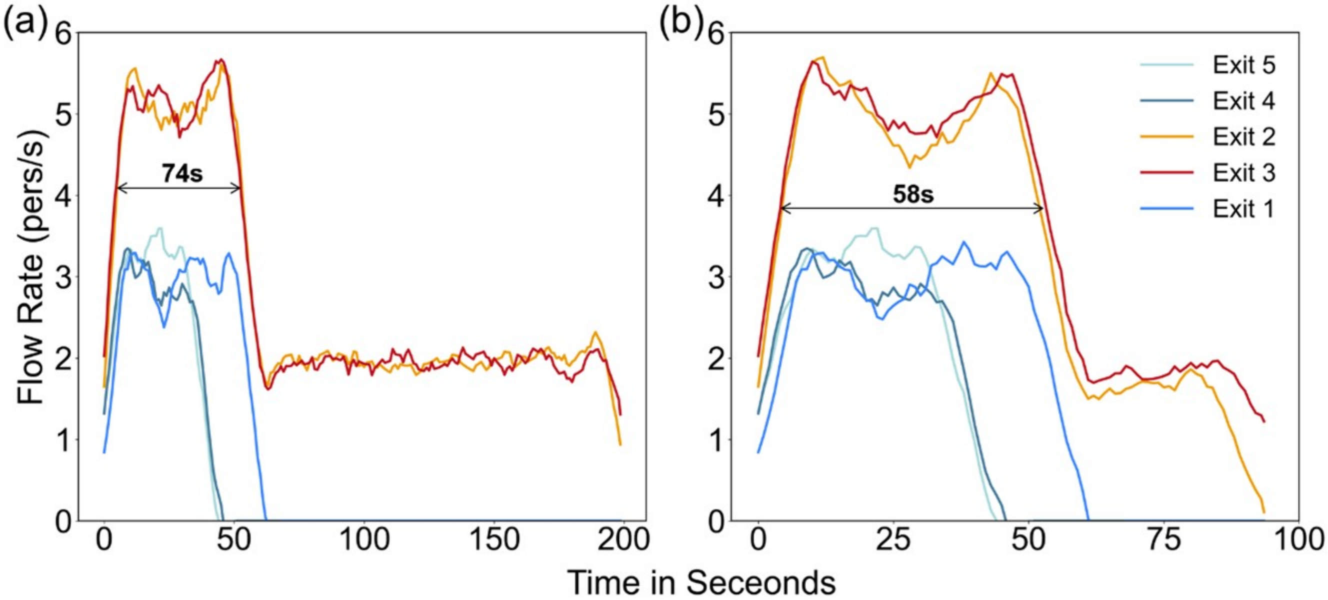

Figure 4. Flow rate at exits during (**a**) the rush hour and (**b**) the daily working hour.

Combined with the analysis of the evacuation process of each floor during peak hours, it is found that the main crowded part is at the stairs on the second floor, which conforms to the evacuation rule. The utilization rate of the five exits is analyzed, and it is found that the width of the south exit plays the most obvious role in the evacuation process.

4.2. Daily Working Hour

During daily working hours, occupants were mainly gathered at the production line on the first floor. At this point, there were 800 people on the first floor, 50 people on the second floor and 200 people on the third floor, respectively. The width of the stairs and the exits were set at 2.5 m and 3 m, respectively.

According to the simulated results, it took 92.5 s for all the occupants to be evacuated to a safe place, which met the specified time requirements. As shown in Figure 4b, under the condition of changing occupants' distribution, the main evacuation pressure was still taken by the south exit, and the maximum flow could reach 5.29 pers/s. The stable period of the south exit appeared after 58.0 s, while the remaining exits "failed" basically. After 58.0 s, the exits were mainly applied for upper-level evacuation.

Comparing the two periods of rush hour and daily working hour, it could be concluded that people would choose the same exits to evacuate even if the distribution and number of occupants were dissimilar. Moreover, there was nearly the same evacuation pressure for the two periods. The reason why the evacuation time during rush hour was twice as long as the daily working hour was mainly correlated to the upper occupants. As Figure 5 presents, the peak value of flow rate would reach 11 pers/s in the daily working hour, while it could be 24 pers/s in the rush hour. There is little difference in the flow rate at each stairway, and Stairway 3 "fails" after 52.0 s in the daily working hour. But it can be found that there is a large difference in the flow rate at each staircase in rush hour, which is mainly due to the congestion of people at Floor 2, and Stairway 3 "fails" after 125 s. Beyond the impact of the exit width, the width of the staircase also had a significant influence on the evacuation process. Notably, it becomes evident that Stairway 1 played a pivotal role in determining the duration of the evacuation process.

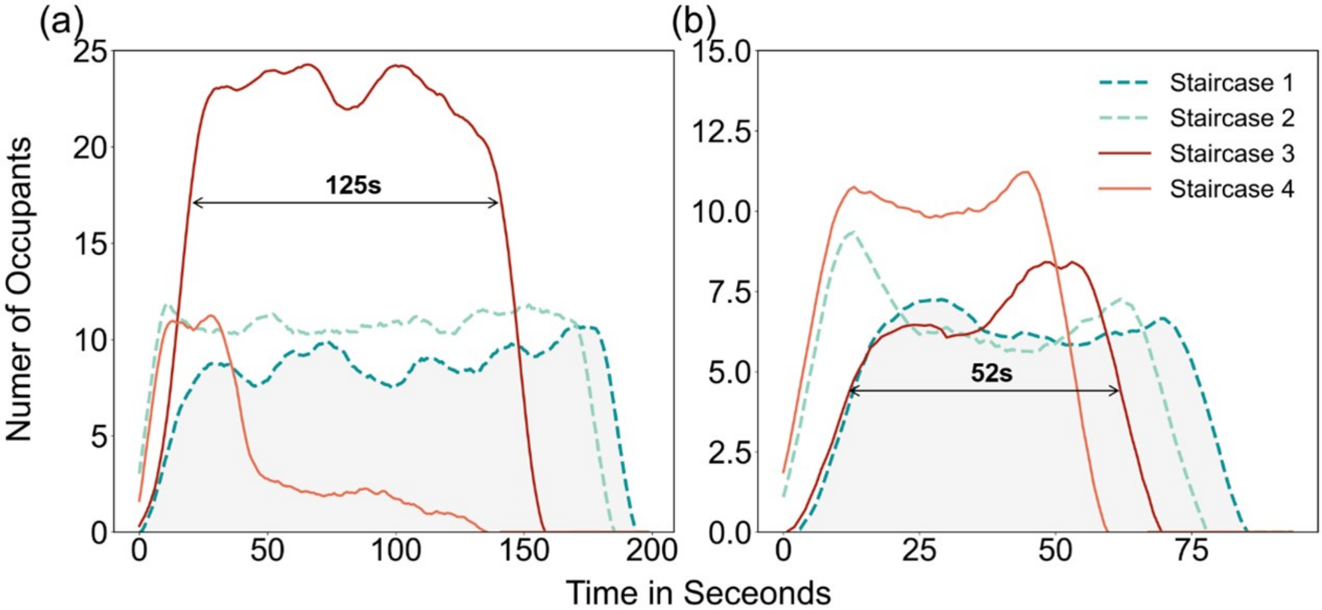

Figure 5. Charts of flow-time in different periods of stairs at (**a**) the rush hour, and (**b**) the daily working hour.

5. Analysis of Influencing Factors

5.1. Change of the Exits Width

Since the evacuation time in the daily working hour proved to meet the requirements of the regulations, this section mainly discussed the evacuation in the rush hour with 800 occupants on the first floor, 600 occupants on the second floor and 100 occupants on the third floor, respectively. Moreover, the width of the stairs was 2.5 m. According to the above analysis, most people would choose the south exit during the evacuation. Therefore, changing the width of the south exit might relieve the evacuation pressure. The south exit was separated and marked as Exit 1 and Exit 2, respectively. From Table 5, when the width of both exits was increased to 5 m, the change in evacuation time was still very small, which had no effect on relieving the evacuation pressure without considering the reasonableness of the building structure. Therefore, the width of the exit was not the main factor affecting the evacuation efficiency [35].

Table 5. The list of evacuation schedules for exits with different width.

Exit 1 Width (m)	Exit 2 Width (m)	Evacuation Time (s)
3	3	200
4	4	198.9
5	5	197

5.2. Change of the Occupant Distribution

According to the above analysis, when the number of people on the first floor was constant and only that on the upper floor was changed, the evacuation time would be reduced by about half. In the case of a fixed total number of people, it would be the focus of the next discussion to change the distribution of people on each floor to reduce the evacuation time. The width of the stairs and the exits were set at 2.5 m and 3 m, respectively.

The main function of the second floor was the occupant's locker room. Considering the real situation, occupants who had not changed their work clothes were not allowed to enter the workshop during the shift. Then, the number of occupants in the production line was kept at 100, and the change in the number was mainly reflected in the rest of the office area connected with the second floor in the distribution of occupants. According to the Chinese standard "Code for Fire Protection Design of Buildings" [36], the stairway effective evacuation width must meet the requirement of 0.8 m per every 100 people. The effective width of the stairway should be greater than 4.8 m for 600 people. As Table 6 indicates, when the number of people on the second floor was about 400, the conditions for safe evacuation could be satisfied. Therefore, the method that restricted the number of occupants entering the second floor in batches could be applied to meet safety conditions.

Table 6. The list of evacuation schedule of different occupant distribution.

First Floor Number	Second Floor Number	Third Floor Number	Evacuation Time (s)
800	600	100	200
900	500	100	183.3
1000	400	100	155.3

5.3. Change of the Stairs Width

According to the previous analysis, when the number of people on the second floor was the maximum, apparent congestion would occur on both sides of the stairway. Thus, in addition to changing the number of people on the second floor, changing the stairs width would also shorten the evacuation time. The numbers of occupants on the first, second, and third floors were set at 800, 600, and 100, respectively, and the width of the exits was 3 m. The width of the staircase was broadened, and the change in evacuation time was observed when the second floor was saturated. From Table 7, only changing the effective evacuation width of the staircase could greatly relieve the evacuation pressure. When the width of the staircase was 3 m, the maximum flow rate of the staircase was as high as 30 pers/s.

Table 7. The list of evacuation schedule of stairs with different widths.

Stairway Effective Evacuation Width/Single (m)	Evacuation Time (s)
2.5	200
3	170.5
3.5	149.5

Further analysis of the staircase connecting the first and second floors showed that the optimal time for adjusting the staircase width to 3.5 m was 150.5 s, resulting in a peak passenger flow of 13 people/s. The peak flow occurred earlier, demonstrating its efficiency, as shown in Figure 6. However, evacuation time met the standard when the width was set at 3 m. The flow rate of the staircase was maintained at the maximum stable stage during 21~154 s, then began to show a downward trend, and it became invalid after about 159 s. Throughout the process, the flow rate from the second to the first floor could reach up to 12 pers/s. Considering the building structure, economy and other factors, increasing the width of each stair was not necessary. However, as the stairs with a width of 2.5 m could meet the local regulation requirements, the evacuation time would be longer than ASET, so 3-meters-wide stairs should be equipped.

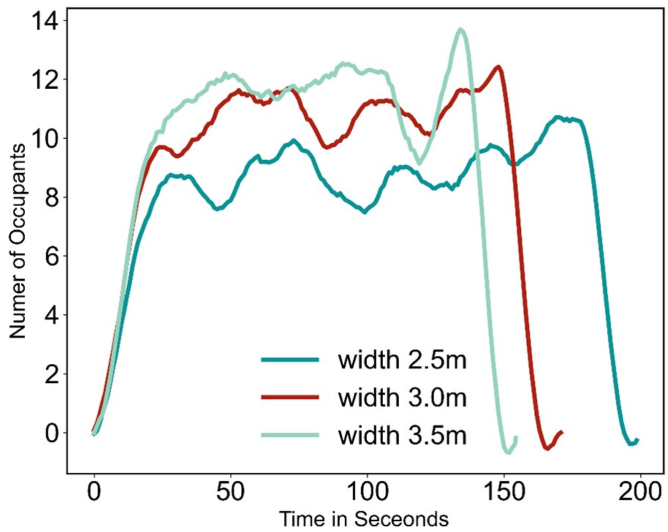

Figure 6. Chart of flow-time when the width of Stairway 1 was 3 m.

6. Conclusions

In this paper, the fire emergency evacuation of a large factory was elucidated, and the effect of exit width, occupant distribution and stair effective evacuation width on the evacuation efficiency was investigated:

1. The original structure of the factory met the safety evacuation conditions during the daily working hours. However, when a fire broke out during the shift, the safe evacuation time was much longer than 174.5 s, which could not meet the requirements of safe evacuation.
2. Merely changing the exit width could not shorten the evacuation time, and it had little effect on alleviating the evacuation pressure without considering the rationality of the building structure.
3. The evacuation time could be effectively shortened by changing the occupant distribution. When the number of people on the second floor was about 400, it could meet the demands of safe evacuation conditions. When applied to practical situations, the number of occupants to entering the upper floor in batches could be restricted.
4. Changing the effective width of stairs to shorten the evacuation time was the fastest and most convenient way. When the width of the stairs was 3 m, the safe evacuation conditions could be satisfied. For every 0.5 m increase in the width, the evacuation time decreased by about 30 s. In addition to meeting the requirements of the regulation, the width of the staircase could be reasonably selected according to the stipulations of the building structure and occupant distribution.

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