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SIMULATION OF THE EVACUATION STRATEGY FOR AN AIR–RAIL INTERMODAL HUB STATION

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Abstract
To clarify the evacuation bottleneck of air–rail intermodal hub stations and improve the efficiency of personnel evacuation, the smoke spread process and the visibility and temperature changes in the case of fire in an air–rail intermodal hub station in Zhengzhou, Henan, China, were simulated via PyroSim simulation software based on performance-based fire protection design technology. The available safe escape time was obtained, the whole process of safe personnel evacuation was simulated, the bottleneck position in the process of evacuation was revealed, and the time required for safe crowd evacuation in the fire environment was determined. Results show that with a smoke exhaust system, smoke spreads to both sides of the hub station in 270 s, the visibility on both sides is affected, and the safe evacuation conditions fail. When the smoke exhaust system does not function, the available safe escape time is 497 s, and the required safe escape time is 370.5 s. The obtained conclusions provide a decision reference for performance-based fire protection design of air–rail intermodal hub stations.

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Key Words: Air–Rail Intermodal Hub Station, Fire Simulation, Emergency Evacuation

1. INTRODUCTION

Air–rail intermodal hub stations involve the joint operation of multiple traffic platforms, such as civil aviation airports, airlines, and railway systems. They can meet the seamless transfer needs of large hub airports and high-speed railways and expand the utilization of air and railway transport. However, hub stations of this kind, such as aboveground hub airports and underground high-speed railways and subways, are mostly public buildings with multistory high-rise space and even underground space. Such hub stations are characterized by evident function zoning, dense personnel distribution, and relatively complicated building space structures. When a fire occurs, personnel evacuation and fire extinguishment are difficult because of the rapid fire spread and diverse spread paths, leading to enormous casualties and seriously threatening the safety of people's lives and properties. The fire situation in various countries worldwide has not been optimistic in recent years. Fire accidents continuously occur in large-scale complex buildings. For instance, on April 29, 2016, a fire took place at the construction site of the Terminal 1 Renovation Project in Shanghai Hongqiao Airport, China; it resulted in two deaths, two severe injuries, and three minor injuries. On May 4, 2018, in a fire accident in Gwangju Metro Line 2 in South Korea, three persons died and others were injured because of the untimely evacuation of passengers. On October 10, 2023, in Luton Airport, London, the UK, all flights had to stop because of a fire disaster in 2# Park Lot of Terminal 2. How to evacuate crowds from the fire field within limited time in the case of fire is one of the important factors related to personnel safety.

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Building fire protection needs to be strengthened and innovated with the help of modern science and technology. Performance-based fire protection design can be combined with fire emergency evacuation during numerical simulations via PyroSim and Pathfinder to realize an objective safety assessment of air–rail intermodal hub stations and scientifically formulate emergency evacuation strategies. In terms of fire emergency evacuation, previous studies have concentrated on passenger stations, metro stations, and high-rise buildings. Personnel evacuation at transfer stations, similar to that at air–rail intermodal hub stations, has been rarely investigated, and performance-based fire protection design of buildings has not been considered in studies on fire emergency evacuation [1]. Moreover, most existing studies were performed through actual drills. The cause and process of fires in large complex buildings are complicated, and personnel evacuation during these events is affected by various uncertain factors. The traditional experimental method is time consuming and costly and cannot produce results on application values. Moreover, safety accidents may be triggered during large-scale crowd evacuation drills. In addition, emergency drills are restricted by the attitude of participants toward drills, system execution, disaster atmosphere, skills and experience, and lassitude during drills, which may result in poor drill effects and failure to reveal the motion laws of personnel evacuation in large complex buildings during emergencies.

To address these limitations, this study simulated an air–rail intermodal hub station in accordance with the performance-based fire protection design of the building. A fire model of the hub station was established via PyroSim and Pathfinder, and its reasonability and feasibility were verified. In addition, the variation characteristics of fire smoke, temperature, and visibility were studied, and the timeliness and reliability of safe evacuation were assessed. An emergency management and disposal plan were also established to provide a reference for performance-based fire protection design.

2. LITERATURE REVIEW

At the methodological level, the research on emergency evacuation has been conducted mainly through crowd experiments and algorithm modelling. In consideration of research safety and experimental ethicality, the experimental research method generally focuses on small-scale evacuation experiments, analyses pedestrian evacuation laws, and extracts relevant parameters by examining the motion characteristics of personnel in experimental scenes. For instance, Wang et al. [2] conducted individual and small-group evacuation experiments in the stairwell of an underground public building to explore the characteristics of individual and small-group upgoing evacuation along the stairway in a scenario with reduced visibility. They analysed the key parameters, such as individual evacuation speed, evacuation behaviour, and small-group characteristics, on stairs and platforms under different visibility conditions. Bernardini et al. [3] invited more than 70 volunteers of different ages to participate in a virtual reality experiment to determine if active and passive emergency guidance systems can help people choose the correct evacuation route in the case of building fire. The results showed that the passive emergency guidance system is highly useful in supporting direction selection, and the active emergency guidance system is effective in one-way paths. Cuesta et al. [4] compared the reaction of individuals and small groups in the face of fire in an evacuation experiment. The experimental results proved that the efficiency of groups is higher than that of individuals, and social factors considerably affect evacuation. Seike et al. [5] experimentally studied the evacuation speed distribution of people walking in tunnels with different levels of smoke distribution in the presence of obstacles, such as cars, on the evacuation route. They concluded that obstacles substantially affect the average and maximum walking speed values but has little influence on the minimum walking speed. Algorithm modelling aims to optimize or plan the evacuation route via mathematical modelling and software analysis. With low requirements for scenes, this method, which is characterized by repeatability, adjustable parameters, and advanced prediction, is better than other experimental methods in terms of research scope and speed, so it is favoured by researchers. Zhang et al. [6] proposed a multistarting point, multiendpoint ripple diffusion algorithm to optimize the emergency evacuation path of crowds in large public places in consideration of capacity limitation. This algorithm dynamically updates the remaining maximum traffic capacity of each link at each moment, adds the ripple waiting behaviour at the node in the case of insufficient traffic capacity, and obtains the path with the shortest evacuation time, including waiting time, from multiple starting points to multiple endpoints at one time. Compared with the traditional emergency evacuation path planning algorithm, this method can reduce the evacuation time of crowds by 8 % on average. Gaitanis et al. [7] considered dynamic characteristics when an emergency occurs and used the graph traversal method to plan the emergency evacuation path. The literature review above shows that scholars have analysed the influence of complex spatial structures and environmental obstacles (such as public building stairwells, high-rise building stairs, presence/absence of confluence, and group decision-making) on evacuation efficiency in the process of dense crowd evacuation mainly via evacuation experiments. The research perspective was mostly a micro one, and the relationship between obstacle avoidance behaviour and evacuation efficiency was revealed by analysing pedestrian motion laws. Large-scale crowd evacuation was rarely discussed from the viewpoint of performance-based fire protection design.

For a simulation and analysis of emergency evacuation in large complex buildings, on the basis of the theory of time-coloured Petri nets, Zhang and Xie [8] modelled the structural characteristics of a building, implemented a performance analysis, rationally planned different evacuation routes for various types of personnel, and performed time simulation of the model to improve personnel evacuation efficiency in the building. The developed method has high evacuation efficiency. Yang and Xie [9] introduced a local performance-based fire protection design for a large station, designed a fire scene, simulated smoke spread via the Fire Dynamics Simulator (FDS), simulated personnel evacuation by using Pathfinder and Simulation of Transient Evacuation and Pedestrian Movements software, performed a fire risk assessment on the basis of the results, and presented fire protection strategies. Meanwhile, Jahedinia et al. [10] simulated the behaviour of passengers carrying baggage in subway and railway transfer stations. The analysis showed that if baggage is not considered, about 28 % of passengers will not evacuate within the simulated and predicted time. Using the butterfly algorithm and social force model, Mao et al. [11] proposed an emergency evacuation simulation path planning method that can effectively use exits and improve evacuation efficiency in multiexit environments. Wei and Liu [12] employed AnyLogic software to simulate the integrated evacuation process, analysed the causes of crowded points and the environmental influencing factors in the simulation process, presented a reasonable plan, and optimized the number of emergency exits opened under different wind directions and the location of personnel sorting areas. The method they developed is conducive to the improvement and implementation of airport emergency plans. Considering that the elderly in nursing homes have weak mobility and cannot evacuate proactively without the guidance of others in the case of fires, Lim et al. [13] adopted an agent-based modelling method to evaluate the effect of the staff's evacuation behaviour on evacuation time during a fire emergency in nursing homes for the elderly. Meanwhile, Choi et al. [14] used the agent-based modelling method to model and analyse the influence of the perceived risk of dynamic emergency information changes on evacuation behaviour in the case of a public building fire. Singh et al. [15] proposed a hybrid building network based on 2.4 GHz Zigbee and LoRa and used it for real-time fire detection and to monitor and help personnel evacuate safely. They implemented the Dijkstra shortest path algorithm in the evacuation path display controller and identified the shortest evacuation route in the case of fires. In summary, with regard to existing evacuation strategies in complex spaces, extant research has focused on the personnel evacuation efficiency and path planning problem and the influence of locally induced changes in personnel behaviour on the evacuation process. Meanwhile, studies on the dynamic planning and organization of large-scale crowds to be evacuated through building performance-based fire protection design from the overall perspective are lacking.

To address the limitations of existing research, this study determined the available safe escape time and the required safe escape time for personnel evacuation in the case of fire through a simulation based on building performance-based fire protection design. The fire risk of an air–rail intermodal hub station was assessed through a comparative analysis, the existing problems were identified, and optimization and improvement measures for the hub station were established. This study can provide guidance for fireproofing installation and safe personnel evacuation in air–rail intermodal hub stations and can help guarantee or improve the fire safety level of similar large complex buildings.

3. METHODOLOGY

3.1 Scene simulation method

Fire scene simulation method: PyroSim is a software developed by Thunderhead Engineering, USA, specifically designed for FDS. Based on computational fluid dynamics principles, the software enables numerical simulation of the movement, temperature, and concentration of toxic gases such as smoke, carbon monoxide, and carbon dioxide in fire scenarios. It supports a wide range of fire simulations, from everyday household fires to indoor electrical equipment and various types of fires. Its standout feature includes 3D graphical pre-processing capabilities and visual editing effects, allowing users to visualize and edit models in real-time, liberating them from the traditionally monotonous and complex command-line interfaces of FDS modelling [17].

Personnel evacuation scene simulation method: Pathfinder is an intuitive, state-of-the-art emergency evacuation assessment tool developed by Thunderhead Engineering in the United States. It employs computer graphics simulation and gaming technology to graphically simulate the movements of individuals within multiple groups during emergencies. Using a grid-based approach, Pathfinder efficiently resolves personnel evacuation challenges in large-scale, complex buildings by accurately determining rapid escape routes and times for each individual during a disaster [18].

3.2 Simulated scene and parameter settings

Simulated fire scene and parameter settings: With an air–rail intermodal hub station in Zhengzhou, Henan, China, as a study case, an experimental scene was set up, and the layout plan of the scene is displayed in Fig. 1. The study object contained a high-speed railway station (14 platforms and 14 line patterns), one airport dispatching floor (4 airport docking sites), and one connection space. The overall layout of the study object presents a “straight shape”. The left side is the waiting hall of the high-speed railway station, the middle part is the air–rail intermodal connecting layer, and the right side is the departure floor of the airport terminal.

(1) The departure level of the high-speed rail station measures 80 m in length, 60 m in width, and 8 m in height. On the left side of the departure level, there are two dedicated ticket checking gates and one security checkpoint. On the right side, there is one air-rail intermodal connection hub, each equipped with entrance and exit points, ticket gates, and security checks. Beyond the ticket gates at the departure level of the high-speed rail station lies outdoor space, which can be considered as safe evacuation points.

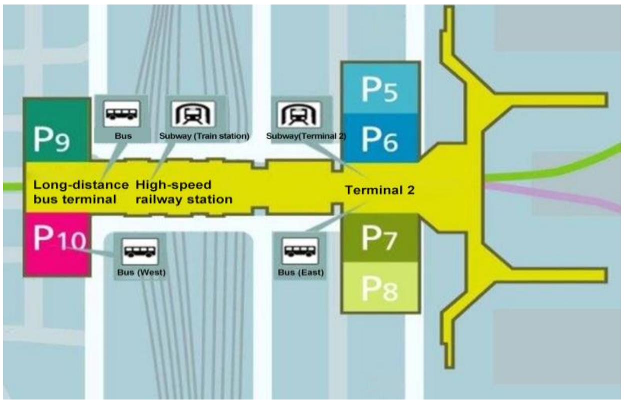


Figure 1: Layout of the air–rail intermodal hub station.

(2) The connection level measures 40 m in length, 10 m in width, and has a height ranging from 8 m to 16 m. The height variation is managed with 50 steps (each step 10 m in length, 0.3 m in width, and 0.16 m in height), including three rest platforms totalling 6 m (each platform 2 m in length). The net height of the connection level is 6 m, with side barriers of 3 m height and open spaces elsewhere. There are 4 entrances/exits on the connection level located at heights of 8 m and 16 m, each 2 m wide.

(3) The departure floor of the airport was set as a small-to-medium-sized terminal building with four parking spaces, and it was divided into a waiting hall, a check-in hall, and a security inspection hall.

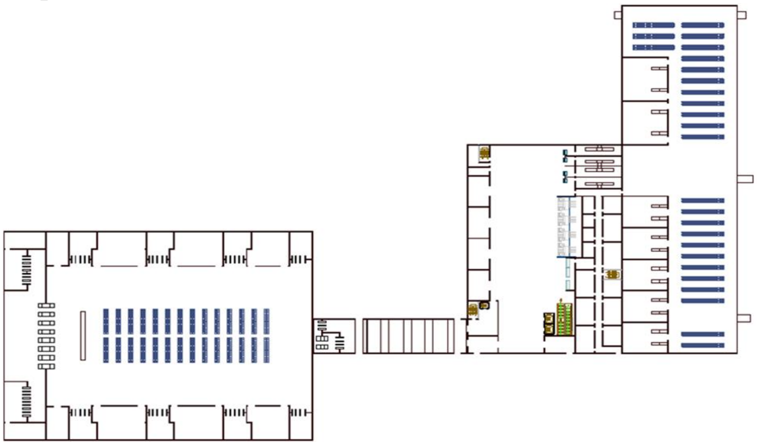


Figure 2: Overall layout of the air-rail intermodal hub station model.

In accordance with the preceding part, a PyroSim fire simulation model was established.

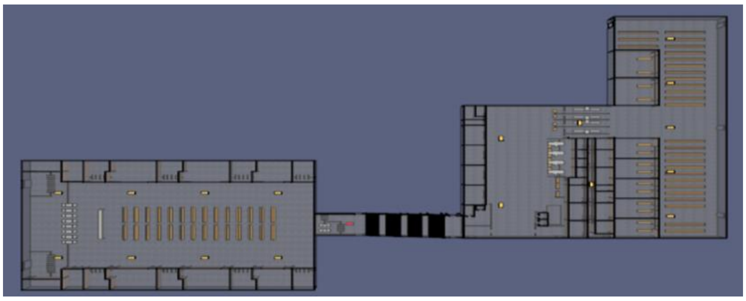


Figure 3. Overall top view of the PyroSim fire simulation mode.

The fire source was set in the middle connection part to ensure the truthfulness and reliability of this study. The fire source could trigger a fire that could affect the left high-speed railway station and the right airport terminal. Specifically, as shown in Fig. 4.

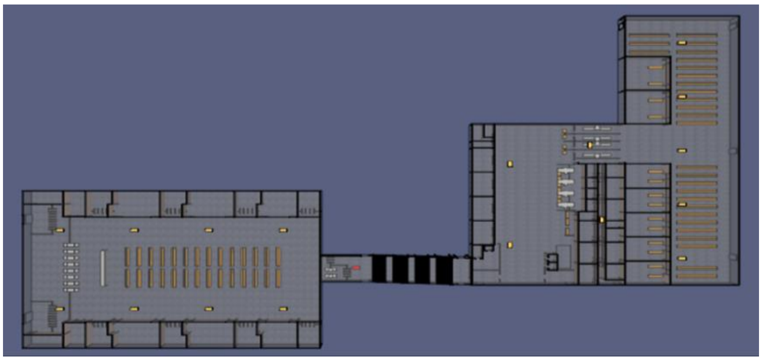


Figure 4: Location of the fire source of the PyroSim fire simulation model.

Fire roller shutters were arranged between the high-speed railway station and the connecting layer and between the connecting layer and the airport terminal for fire separation to ensure that smoke would not spread. According to the provisions in Article 4.2.4 of the *Technical Standard for Smoke Management Systems in Buildings* (GB51251-2017), the maximum allowable area should not exceed 2,000 m^2. Therefore, the area of each smoke control zone was set to about 600 m^2 (20 m × 30 m), and smoke exhaust facilities were set up in accordance with the provisions. The failure mode of the fire roller shutters (i.e., fire and smoke could spread freely) was used to simulate the most adverse fire scene.

All FDS operations were implemented in the divided meshes. In the simulation process, every obstacle and vent must conform to the meshes, so the whole simulation process will be directly affected by the mesh generation in the computational domain. In this study, FDS operations were implemented using the resolving program based on fast Fourier transform. After the calculation of each mesh, data were transmitted to peripheral meshes through six faces. The smaller the meshes generated are, the larger the number of meshes is and the higher the accuracy of the simulation results is. However, the calculation time considerably increases to $2^4 = 16$ times the original time because of the increase in the number of calculation steps after mesh dichotomy. Meanwhile, high requirements were used for the computer equipment configuration. A 1 m × 1 m × 1 m network pattern was adopted for mesh densification at the fire source, and a 1 m × 1 m × 1 m mesh layout was applied to the other parts to ensure a fast, accurate design process. The total number of meshes was nearly 100,000.

In the fire simulation model, smoke, temperature, and visibility detectors were set at each evacuation exit to ensure the available safe escape time, and the height of the human body was considered. According to previous studies, three criteria can be adopted to judge critical fire danger conditions. The first one is smoke. When the height of the hot smoke layer is below the height of human eyes by 1.2–1.8 m (1.6 m in this study) in general, danger is imminent. The second criterion is temperature. The human body can be directly burned or injured when hot air at the critical temperature of 70°C is inhaled. The last criterion is visibility. For two-story indoor spaces, visibility less than 10 m is considered a dangerous state.

In the fire simulation model of this study, the monitoring faces of fire parameters were set to a height of 10.6 m from the ground of each floor to monitor fire smoke visibility and temperature, and two fire scenes were set as follows: absence (fire scene 1) and presence (fire scene 2) of smoke exhaust facilities.

Personnel evacuation simulation scene and parameter settings: In actual fire evacuation, the efficiency of personnel evacuation is affected by various uncertain factors, including the familiarity of individuals with building structures, their vigilance and perception, their mobility, and the layout of fire safety evacuation equipment. Therefore, the evacuation time, t_{move}, obtained by simulation calculation is usually multiplied by safety factor k, whose value is usually between 1.2 and 1.5 [19]. In this study, 1.5 was selected as the correction factor, and the calculation formula of the time required for safe personnel evacuation ($RSET$) is as follows:

$$T_{RSET} = t_{\mathrm{det}} + t_{resp} + kt_{move} \tag{1}$$

where t_{det} is the alarm time, t_{resp} denotes the preparation time for personnel evacuation, and t_{move} stands for the total time spent by all passengers in the air–rail intermodal hub station from the moment start to move until they reach a safe state.

The fire is detected by people near the ignition point at the early stage because the terminal and high-speed railway station of the air–rail intermodal hub station have automatic fire alarm systems, and the number of departing passengers is large. In the most unfavourable scenario, the fire is detected by the alarm system only after 60 s. Therefore, in this study, t_{det} was set to 60 s.

Generally, at the early stage of a fire, the fire is noticed by people around it, and the fire information spreads rapidly among people. However, passengers in a terminal do not know the safe escape route of the building. According to relevant information, the evacuation time of people should not be less than 1 min in leisure centres, shopping malls, and exhibition halls (people are conscious and unfamiliar with the building). Therefore, in this study, t_{resp} was set to 60 s.

The density of personnel in the high-speed railway station was set to 1 m^2/person by referring to relevant research norms and standards. The high-speed railway station covered an area of 4,800 m^2, and the number of personnel to be evacuated was estimated to be 4,800 (including the staff). The maximum personnel density in the terminal was 3 m^2/person, and in consideration of the most unfavourable situation, it was increased by 50 %. Hence, the final personnel density was 2 m^2/person. The terminal covered an area of 5,400 m^2, and 2,700 people were to be evacuated. The connecting layer was a capped escalator with an area of 400 m^2, and the number of personnel to be evacuated was estimated to be 200. In this study, a total of 7,700 personnel needed to be evacuated.

The actual motion time of evacuation was calculated by simulation software. An evacuation model was also established via Pathfinder, as illustrated specifically in Fig. 5 below.

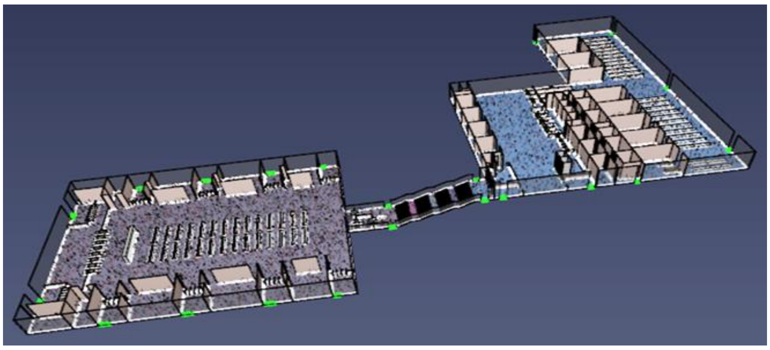


Figure 5: Top view of personnel evacuation.

In summary, the waiting hall in this study is equipped with two entrances and exits with evacuation widths of 3.6 m each, while the platform level has 8 evacuation points (3 m, 3 m, 3 m, 3 m, 3 m, 3 m, 2 m, 2 m). The connection level has four evacuation points (2 m each), and the check-in and security hall have a total of three safety exits (2 m, 2 m, 1.5 m) and two evacuation staircases (1 m, 1.2 m). The waiting lounge has four boarding gates (2 m each) for evacuation.

In addition, human movement speed directly influences evacuation rate. Due to carrying luggage, passengers move slightly slower when exiting compared to normal circumstances. The average evacuation speeds of business travellers are detailed in Table I [20]. This study considers real-world scenarios, employing average speeds, with 25 % of males carrying luggage, 25 % of males without luggage, 25 % of females carrying luggage, and 25 % of females without luggage for simulation purposes.

Table I: Average evacuation speed of business travellers.

	Highest speed (m/s)	**Lowest speed** (m/s)	**Average speed** (m/s)
Males carrying baggage	1.47	0.76	1.12
Females carrying baggage	1.36	0.74	1.03
Males not carrying baggage	1.50	0.89	1.17
Females not carrying baggage	1.25	0.79	1.09

4. RESULT ANALYSIS AND DISCUSSION

4.1 Simulation results and analysis

Fire simulation results and analysis: The fire spread situation was analysed by selecting the simulation result with the smoke exhaust effect (fire scene 2):

(1) A schematic of the smoke changes is displayed in Fig. 6. Ninety seconds after the fire broke out, the smoke did not spread to the left side of the high-speed railway station nor the right terminal. At 180 s, the smoke spread toward the two sides. At 270 s, the smoke engulfed the total area covered by the station. These results indicate that the effect of smoke became increasingly serious with time.

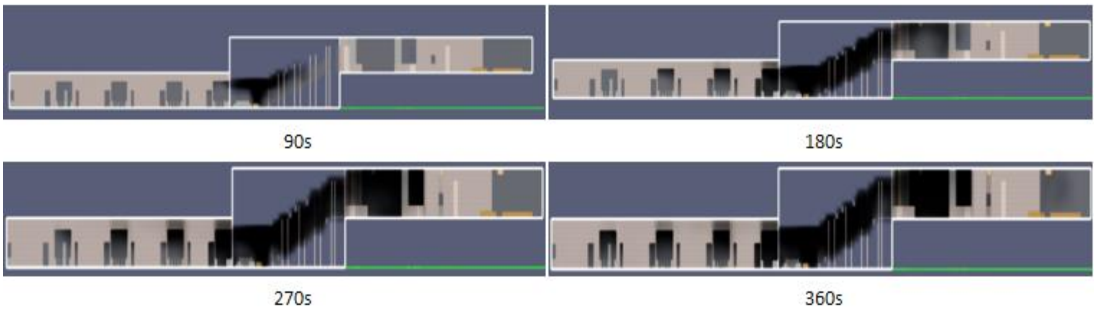


Figure 6: Schematic of the smoke changes.

(2) A schematic of the visibility changes is displayed in Fig. 7. As shown above, 90 s after the fire broke out, visibility started to decline. At 180 s, visibility affected the whole connecting layer, and at 270 s, the visibility on both sides was affected. These results indicate that visibility changed with time.

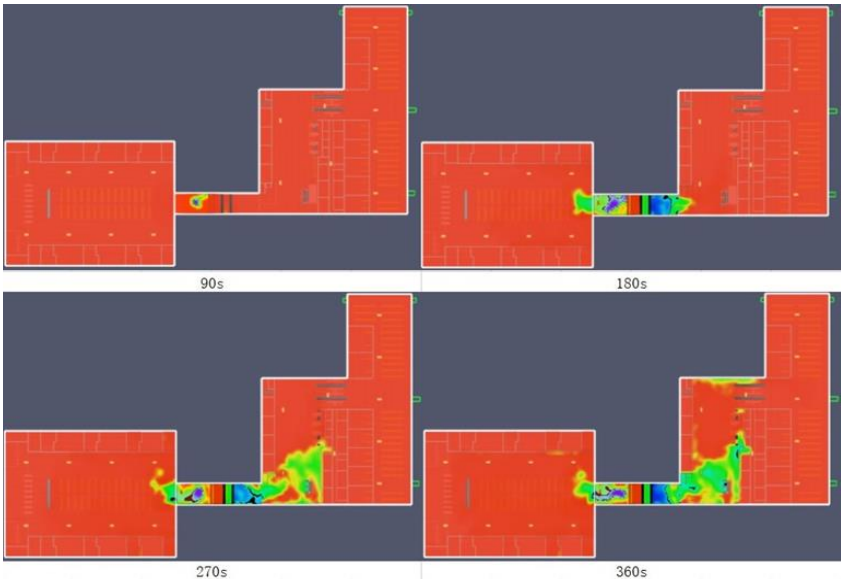


Figure 7: Schematic of the visibility changes.

(3) A schematic of the temperature changes is shown in Fig. 8, which reveals that when the fire occurred, the temperature change over the passage of time was not evident.

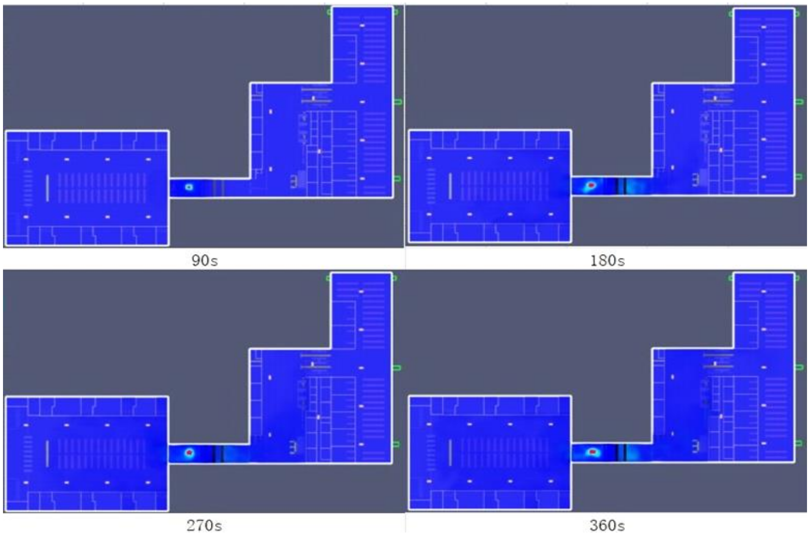
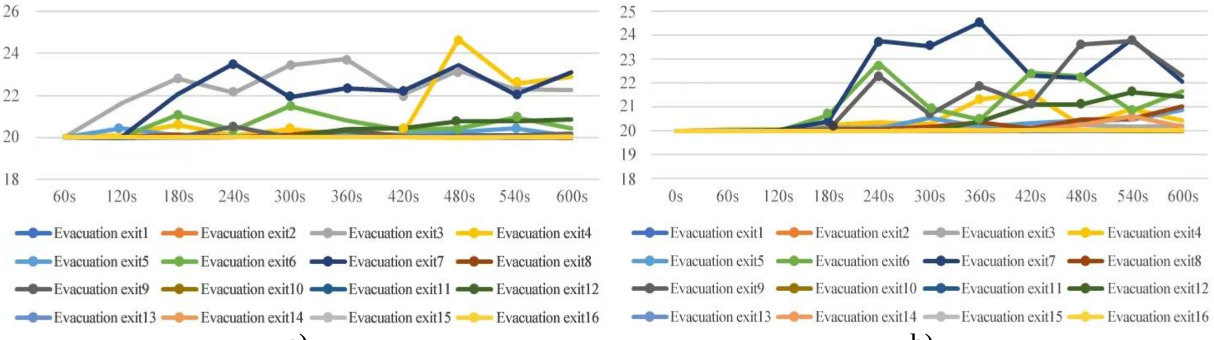


Figure 8: Schematic of the temperature changes.

(4) Analysis of the spread of smoke, visibility, and temperature indicated that after the fire broke out, it quickly spread along the corridor of the connecting layer. However, because the smoke in the terminal was high and spread easily, it fanned out to the terminal rapidly and widely, leading to the fast decline in visibility in the terminal. Meanwhile, the temperature rise in the other zones, except for the zones around the fire source, was not evident because of the small fire load.

(5) Comparison of temperatures at the different evacuation exits under fire scenes 1 and 2. Refer to Fig. 9 for specific details. The comparison of the temperatures at the different evacuation exits showed that the temperature at each evacuation exit did not rise to the critical risk value.



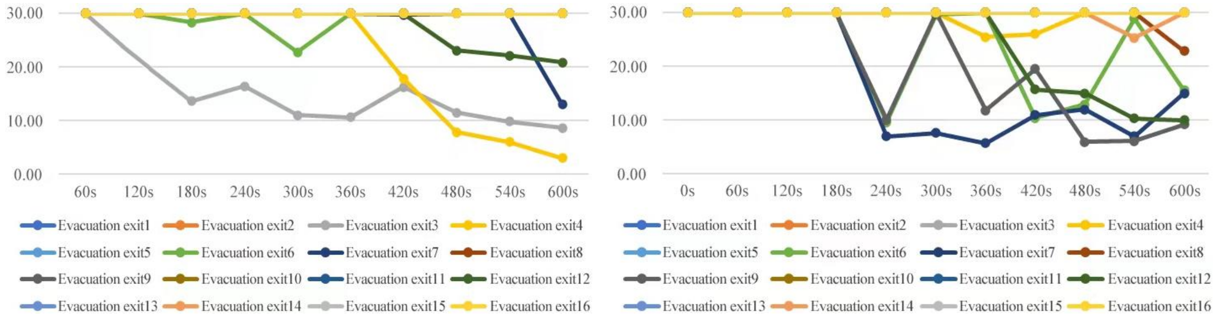
a) b)

Figure 9: Comparison of the temperatures at the different evacuation exits: a) with smoke exhaust facilities; b) without smoke exhaust facilities.

(6) Comparison of visibility at the different evacuation exits under fire scenes 1 and 2. Refer to Fig. 10 for specific details. The visibility at the evacuation exits decreased to the critical value, and this effect was evident in the case without smoke exhaust facilities. Furthermore, an obvious evacuation effect was achieved by setting smoke exhaust facilities. Hence, the decline in visibility to 10 m was adopted as the judgment criterion for available safe escape time.

(7) The influence of available safe escape time obtained by comparing the data for fire scenes 1 and 2 is shown in Table II. The available safe escape time in the scenes involving the normal operation of the smoke exhaust system was effectively shortened relative to that in the

situation where the smoke exhaust system failed. In the former, the evacuation time for personnel was sufficient, thus elevating the fire safety level of the terminal from the perspective of facilities.



a) b)

Figure 10: Comparison of visibility at the different evacuation exits: a) with smoke exhaust facilities; b) without smoke exhaust facilities.

Table II: Influence of failure state of the smoke exhaust system on available safe escape time.

Operating state of the smoke exhaust system	**Available safe escape time** (s)
Normal	510
Failure	497

Personnel evacuation simulation results and analysis:

(1) The evacuation simulation results were calculated by selecting the maximum evacuation time of 220.5 s.

Total time spent by all personnel in the high-speed railway station on running to the safety exits: t_{move} = 150 s;

Time spent on completing personnel evacuation on the connecting layer: t_{move} = 40 s;

Time spent on completing personnel evacuation in the airport terminal: t_{move} = 220.5 s.

The following can be solved with Eq. (1):

$$T_{RSET} = 220.5 + 60 + 1.5 \times 60 = 370.5 \text{ s}$$

The total required evacuation time in this study was 370.5 s, and when the most unfavourable factors were considered, the available safe escape time without smoke exhaust facilities was 497 s. The required safe escape time was less than the available safe escape time, namely, $T_{RSET} < T_{ASET}$, indicating safe evacuation.

(2) Analysis of the scene of personnel evacuation after the fire broke out revealed that personnel were affected by airport partitions, security checkpoints, and other equipment and had to cross multiple obstacles to evacuate, which considerably affected the evacuation time. Furthermore, the personnel in the internal equipment room were far from the evacuation exits, so the evacuation time increased substantially.

Meanwhile, the model comparisons showed that the partitions in the airport terminal were complicated, and personnel clustered together during evacuation, considerably aggravating the difficulty of evacuation. Hence, attention should be paid to the identification of evacuation-indicating equipment and the reasonability of evacuation design in airport terminals.

5. CONCLUSIONS

This study examined the fire danger and safe personnel evacuation of an air–rail intermodal hub station, which was a large, tall building. The available safe escape time (*ASET*) was obtained by PyroSim-based simulation through performance-based fire protection technology under the pre-set fire scene. Then, the required safe escape time (*RSET*) was simulated via

Pathfinder under the corresponding evacuation scene. The safety of personnel evacuation was analysed by combining the available safe escape time and the required safe escape time. The following conclusions were obtained:

(1) The fire process in the air–rail intermodal hub station was simulated using PyroSim fire simulation software, and the process parameters of the large-scale transport hub station in the set fire scene were analysed. The results showed that 270 s after the fire broke out, with the presence of smoke exhaust facilities, the smoke spread to both sides, and the visibility on both sides began to be affected.

(2) Comparison of the simulation results for fire scenes 1 and 2 revealed that the available safe escape time was 510 s when the smoke exhaust system worked normally and 497 s when the smoke exhaust system failed.

(3) The evacuation process under this model was simulated and evaluated using Pathfinder. From the analysis of the factors that affected personnel evacuation (e.g., the characteristics of the building structure and personnel behaviour characteristics in the evacuation process), specific data were obtained. First, 150 s passed before all personnel in the high-speed railway station reached the safety exits, 40 s passed before the personnel in the connecting layer could evacuate, and 220.5 s passed before the personnel in the airport terminal could evacuate. Second, the required safety escape time was 370.5 s, which meets the safety standard.

In summary, PyroSim and Pathfinder personnel evacuation simulation software can be used to effectively analyse the fire risk and crowd evacuation efficiency in large complex environments, such as air–rail intermodal hub stations, and identify the bottleneck position in the evacuation process. With performance-based fire protection design, a safe and efficient evacuation strategy can be formulated based on the location distribution of emergency exits in different spatial structures. This strategy provides a time guarantee for emergency management and safe rescue work in air and railway transportation.

In the simulation model established in this study, the fire scenes were set simply, and basic data, such as crowd density, personnel characteristics, and crowd social force effect in the process of evacuation, were incomplete and thus need to be supplemented by additional basic studies. If such data are supplemented, the results will become highly authentic and convincing. The abovementioned study limitations serve as follow-up research directions.

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