Int j simul model 23 (2024) 3, 435-446
Original scientific paper

AN OPTIMIZATION METHOD OF LARGE BUILDING SPACE BASED ON EVACUATION SIMULATION

Shen, N. Z.[*,**]; Cui, J. W.[*,**]; Peng, M.[*,**]; Xu, H.[*,**] & Wu, Z. Q.[*,**,#]
[*] School of Safety Science and Engineering, Changzhou University, Changzhou, 213164, China
[**] Institute of Public Safety and Emergency Management, Changzhou University, Changzhou, 213164, China
E-Mail: wzq0323@cczu.edu.cn ([#] Corresponding author)

Abstract
To improve crowd evacuation efficiency in large building spaces during fires, a spatial layout optimization method using PyroSim and Pathfinder software was proposed. Disaster-causing factors that hinder safe evacuation – such as smoke spread, fire scene temperature, CO concentration, and visibility – were compared. The arrival time of danger in fire environments was analysed, the time required for crowd evacuation was calculated, structural characteristics of building space affecting evacuation efficiency were identified, and evacuation bottlenecks in large-scale buildings were revealed. Taking the super-large building of Silk Clothing City in Jiangsu Province, China as an example, a spatial layout optimization scheme focused on evacuation efficiency was proposed and its effectiveness was verified. Results show that before spatial layout optimization, the available safe evacuation time is 145 seconds, which is shorter than the required safe evacuation time of 197.8 seconds, indicating high safety risks during evacuation in a fire. After optimizing the layout of smoke exhaust equipment, the available safe evacuation time is increased to 205 seconds, substantially enhancing crowd evacuation safety.
(Received in June 2024, accepted in August 2024. This paper was with the authors 2 weeks for 1 revision.)

Key Words: Fire in Large Buildings, Spatial Layout Optimization, Evacuation Efficiency

1. INTRODUCTION

In recent years, fire incidents worldwide have been severe, with high numbers of fires, casualties, and property losses. In 2022 alone, fire rescue teams in China responded to 825,000 fires, resulting in 2,053 deaths, 2,122 injuries, and direct property losses amounting to RMB 7.16 billion [1]. Assembly occupancies, including large complex buildings like shopping malls and convention centres, account for a substantial portion of these casualties and economic losses. These buildings present high fire risks because of dense crowds, complex structures, numerous flammable materials, and extensive electrical equipment. Fires in shopping malls, for example, can cause rapid combustion of flammable items like clothes and plastics, leading to the swift spread of smoke and harmful gases, complicating evacuation and often resulting in mass casualties and injuries. Large commercial buildings are characterized by extensive areas, complex spatial structures, and numerous facilities and obstacles, all of which hinder efficient crowd evacuation during fires. Fire accidents in such buildings can lead to severe consequences, including mass casualties and substantial property losses [2]. Therefore, analysing fire spread trends in large buildings, evaluating fire evacuation safety, and optimizing spatial layouts are crucial measures to improve evacuation efficiency in large complex spaces.

Existing research on fire emergency evacuation and spatial layout optimization in large complex buildings has primarily focused on evacuation drills, emergency plans, and path planning [3]. The typical research approach involves analysing crowd flow channels within large buildings to assess the reliability and safety of evacuation during fires. Subject modelling for spatial layout optimization has often utilized technologies like CAD and BIM, incorporating concepts of functionality, structuredness, sustainability, and economy to explore the layout and structure of large buildings from a macro perspective [4]. However, few studies have addressed the safety issues and optimization methods for spatial structures in large buildings based on fire

emergency evacuation efficiency. In addition, emergency evacuation bottlenecks have generally been analysed through emergency drills. In complex buildings with numerous fire-causing factors and complicated fire spread processes, evacuation is influenced by multiple uncertain spatial structures, reducing the universality of research results. Traditional experimental methods and large-scale drills are resource-intensive and often fail to yield practical results or reveal the dynamics of evacuation in emergencies [5]. To address these issues, this study combines spatial layout optimization design with fire emergency evacuation simulation using PyroSim and Pathfinder numerical methods. By exploring fire-induced smoke temperature, CO concentration, and visibility, this study evaluates the safety of evacuation in a large shopping mall. Based on the fire safety analysis of the large building, this study proposes a scientifically grounded internal spatial layout optimization strategy and verifies its feasibility and reasonability. This research aims to provide a theoretical reference for evaluating evacuation safety and formulating emergency management strategies in large buildings during fires.

2. LITERATURE REVIEW

In analysing factors influencing fire emergency evacuation, existing studies mostly focus on crowd evacuation efficiency through the behavioural response of evacuees, evacuation speed [6], alarm system, and evacuation strategy [7]. For example, Schmidt-Polonczyk et al. [8] conducted evacuation experiments considering slope, human fatigue, and visibility to explore the coupling influence of complex tunnel fire environments on evacuation speed. They revealed the influencing laws of single and multiple coupling factors and proposed a simulation calculation method for evacuation speed in fire scenarios. Mossberg et al. [9], aiming to improve evacuation efficiency in subway stations post-fire, analysed the interaction between panic and evacuation behaviour using a cellular automata model that considers dynamic changes in individual panic, and established a simulation model for fire evacuation in subway stations. Gwynne et al. [10] developed a theoretical framework based on individual decision making and emergency response by modelling evacuation behaviour and evacuation exits during a fire. Gerges et al. [11] conducted evacuation experiments to test the effects of fire alarms, visibility, and emergency exit signs on fire evacuation efficiency in building spaces, concluding that fire alarms, visibility, and emergency exit signs markedly enhance evacuation efficiency. Krol and Krol [12], considering factors such as fire detection delay, ventilation system type, traffic conditions, fire sites, and firefighting power, combined experimental analysis with numerical simulation to analyse the formation of evacuation bottlenecks and congestion, proposing an analytical model for fire-caused crowd movement in fire scenarios. Overall, although factors affecting evacuation efficiency during fires have been extensively analysed, the restriction of crowd evacuation efficiency by internal spatial layouts of buildings has been scarcely explored. The formation mechanism of bottlenecks during crowd evacuation in different buildings with varying spatial layouts remains largely unexamined. Defining and optimizing the internal layout of building spaces is an effective method for improving fire evacuation efficiency in large buildings.

In terms of research methods, previous studies have analysed fire evacuation problems through complex mathematical modelling, numerical simulation design [13], evacuation behaviour experiments [14], and proposed emergency management strategies. For instance, Yuan et al. [15] examined the persuasive effect of staff during fire evacuation in large buildings by setting fire safety awareness, behaviour choice motivation, and fire cognitive ability as mediator variables, and analysed the influence relationship between evacuation efficiency and staff evacuation effects using structural equation modelling (SEM). Yuan et al. [16] studied temperature and smoke spread laws during fires in large buildings with incomplete firefighting

equipment, analysing the influence of chimney effect and pumping action on smoke distribution. Wang et al. [17], based on the identification of fire source locations, proposed a multi-exit selection model for crowd evacuation and discussed the distribution of evacuation bottlenecks in different areas of a large shopping mall. Yen et al. [18], considering temperature changes in different areas of a multi-story multi-exit building, proposed a temperature-sensing-based intelligent algorithm for fire evacuation paths and verified the scientific validity of these paths. Krasuski and Krenski [19] explored interactions among probabilistic evacuation methods, automatic exit route planning, and evacuee movement using the fire risk evaluation software Aamks. Shoshe and Rahman [20] analysed how different spatial structural layouts in a large shopping mall affect fire capacity and smoke spread, examining hazards formed by different types of fire on the geometric structure of building spaces. In summary, existing research on fire evacuation in large buildings has predominantly focused on personnel management, risk assessment, and evacuation route planning. Although fire risks in large buildings have been extensively studied from various perspectives, these studies often fail to fully capture the dynamic disaster-causing processes and formation mechanisms in fire systems. Although the effect of spatial structure on evacuation efficiency has been investigated to some extent, the complexity of large building spaces and the diversity of evacuated crowds limit the practical applicability of proposed spatial optimization strategies.

Given these limitations, this study explores an optimization method for the internal spatial layout of large complex buildings from a safety management perspective. This method is based on analysing fire risk, fire scene temperature, visibility, and smoke spread, and employs simulation calculations to evaluate evacuation efficiency. Numerical simulations were used to determine the available safe evacuation time and the required safe evacuation time in the event of a fire in a large building. Optimization strategies for the internal spatial layout of the building were then proposed, and their reasonability and effectiveness were verified.

3. METHODOLOGY

3.1 Fire analysis and simulation method for large buildings

Smoke spread: Combustion produces a substantial amount of smoke, which, being less dense than air, rises to the top of the building. As the fire progresses, the volume of smoke increases and its height decreases, impeding evacuation. H_C is the critical height of smoke posing a danger to evacuees. The hazard level of smoke is determined using Eq. (1) [21].

$$H_s < H_c = H_p + 0.1H_b \tag{1}$$

where H_S is the critical dangerous height of the smoke layer, H_p is the average height of human eyes in smoke, and H_b is the net height of building stories.

Smoke visibility analysis: Visibility is the maximum distance at which people can distinguish a target from its background. Fire produces smoke that reduces visual range and irritates the eyes, impairing vision and evacuation. According to the *Austrian Guide for Fire Protection Engineers*, the critical value of visibility in large spaces is set to 10 m in this study.

Smoke temperature analysis: Accurate assessment of the human body's tolerance to high temperatures is crucial in fire analysis. Rapid increases in smoke temperature can cause burns, further complicating evacuation. According to NFPA standards, the temperature tolerance limit for human bodies during evacuation is 60 °C, with the average temperature needing to remain below 49 °C in the first 6 min. If temperatures exceed 65 °C, discomfort occurs, affecting escape and rescue efforts.

CO concentration simulation: CO is the primary harmful gas in smoke from building fires and a major cause of fatalities. The concentration of CO from common building material

combustion can reach 2.5 %. At a concentration of 0.1 %, CO can cause dizziness, nausea, and poisoning [22]. Therefore, the critical dangerous CO concentration in this study is set to 0.1 %.

In this study, the fire risk simulation was conducted using Silk Clothing City, a large building space in Jiangsu Province, China, as a case study. Silk Clothing City located at Suzhou city, covers 100,000 square meters, hosts nearly 2,000 commercial tenants, and employs approximately 30,000 people, making it one of the largest commodity trading parks in the province.

The building dimensions are: 206 m in length, 172 m in width, and 4.2 m in height. A CAD model of the building was created according to the plan and imported into PyroSim software, constructing a 1:1 scale 3D fire simulation model. To ensure accuracy, the mesh size was set to 1 m × 1 m × 1 m, resulting in 376,740 total meshes, with 230 × 183 × 9 selected meshes. Fig. 1 provides the side view of the fire simulation for Silk Clothing City.

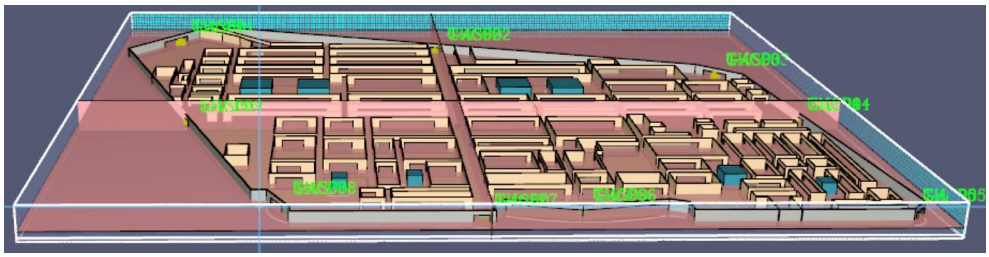


Figure 1: Side view of fire simulation of Silk Clothing City.

In fire simulation, selecting the location of the ignition point is critical. For this study, the ignition point was set at the intersection of the central aisle, chosen for its high crowd density and many stores, and its relative distance from all exits, based on the most dangerous principle in safety engineering. The area was characterized by high crowd density and many stores, and it was relatively distant from all building exits, increasing evacuation difficulty.

According to the China national standard for fire heat release rate, the heat release rate for large building spaces without spraying facilities is 10.0 MW/m^2. The ignition point was set as a 1 m × 1 m × 1 m cube with a total surface area of 6 m^2 and a heat release rate of 10,000 / 6 = 1666 W/m^2. Visibility slices were set at 2 m from the ground, and temperature slices at $X = -96$ m and $Y = -38$ m. Temperature sensors and CO concentration sensors were arranged at each exit for the fire simulation analysis.

3.2 Crowd evacuation simulation method

For crowd evacuation safety analysis, the internationally recognized calculation standard for safe evacuation time is [23]:

$$ASET \geq REST \tag{2}$$

where *ASET* stands for the available safe evacuation time, which refers to the time when evacuees are physically and psychologically affected. *REST* stands for the required safe evacuation time, the total time needed for everyone in the building to evacuate to a safe area.

The efficiency of evacuation is influenced by factors like familiarity with building structures, vigilance, perception, action ability, and fire safety evacuation equipment layout. The calculation formula [23] for *REST* is:

$$T_{REST} = t_{\det} + t_{resp} + kt_{move} \tag{3}$$

where t_{det} is the alarm time, the time from the fire occurrence until the alarm system detects the fire and sends a signal; t_{resp} is the preparation time for evacuation, the interval from receiving the fire alarm signal or confirming the fire until evacuation begins. For this study, t_{resp} is set to 30 s. t_{move} is the total movement time from the start of evacuation until reaching a safe area.

The building CAD model was imported into Pathfinder evacuation simulation software to create a 1:1 evacuation simulation model. Nine safe evacuation exits, store doors, elevators, and warehouses were set according to the building layout. Evacuation routes and obstacles were arranged based on actual conditions.

In accordance with the *Code for Fire Protection Design of Buildings* and *Human Dimensions of Chinese Adults*, the number of personnel, distribution, step speed, height, shoulder width, and evacuation paths for large building spaces are set as shown in Table I.

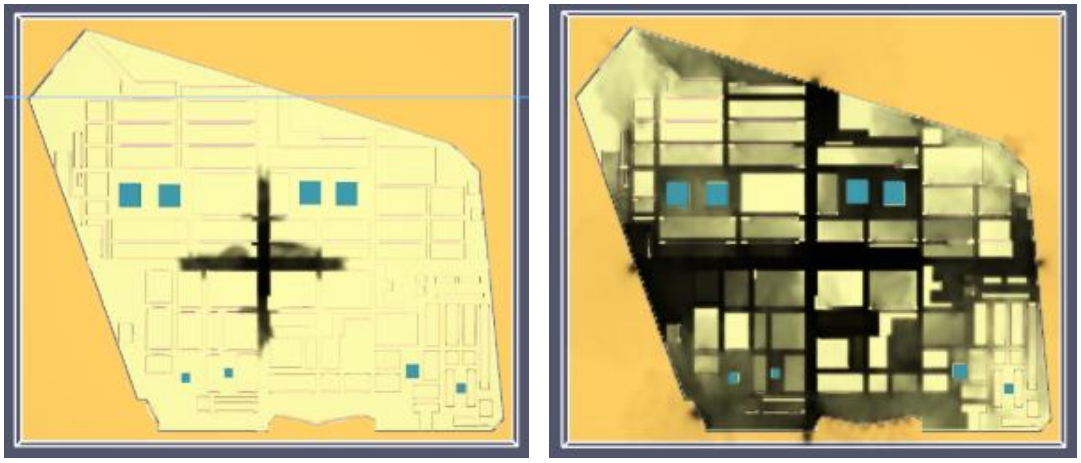
Table I: Evacuation parameters for large building spaces.

Evacuation parameters	Value setting
Number of personnel	8259
Moving speed	1.19 m/s
Body height of personnel	165 cm
Shoulder width	0.45 m
Distribution mode	Random distribution
Evacuation path	Go to any exit

4. RESULT ANALYSIS AND DISCUSSION

4.1 Analysis of PyroSim-based fire simulation results

Smoke spread analysis and simulation: Fig. 2 illustrates the fire smoke spread in the study object. The slices depict the smoke diffusion at 30 s and 360 s. At 30 s, a small amount of smoke was generated at the fire source and began spreading in the aisles. At 90 s, the smoke spread to the four main safety exits. At 270 s, all aisles and stores were filled with smoke. At 360 s, when the simulation ended, the entire building was filled with smoke, which started spreading to the outside.

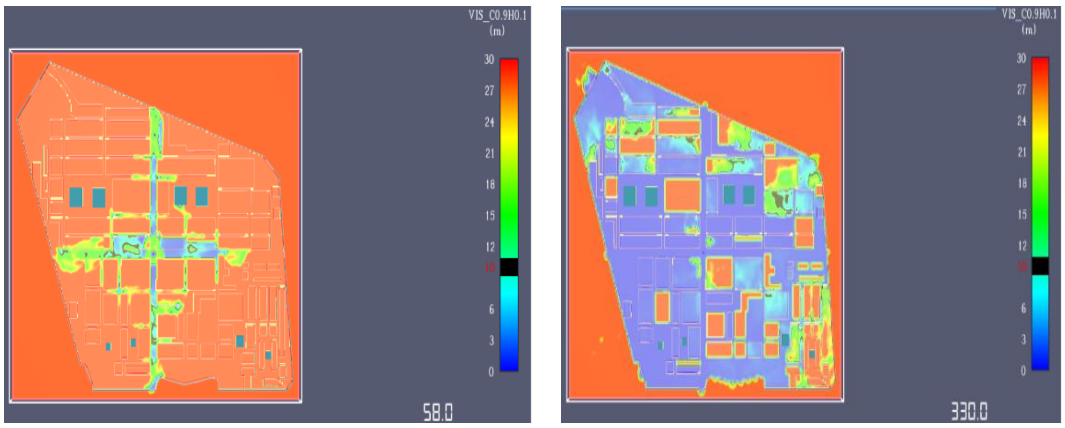


a) Smoke spread state at 30 s b) Smoke spread state at 360 s

Figure 2: Simulation results of fire smoke spread.

Smoke visibility simulation: Considering the characteristics of evacuees, H_p was set at 1.6 m; the net height of the building, H_b was set at 4.2 m. According to Eq. (3), $H_C = 1.6 + 0.1 \times 4.2 = 2.02$ m. Therefore, the smoke height of 2 m was set as the critical dangerous height.

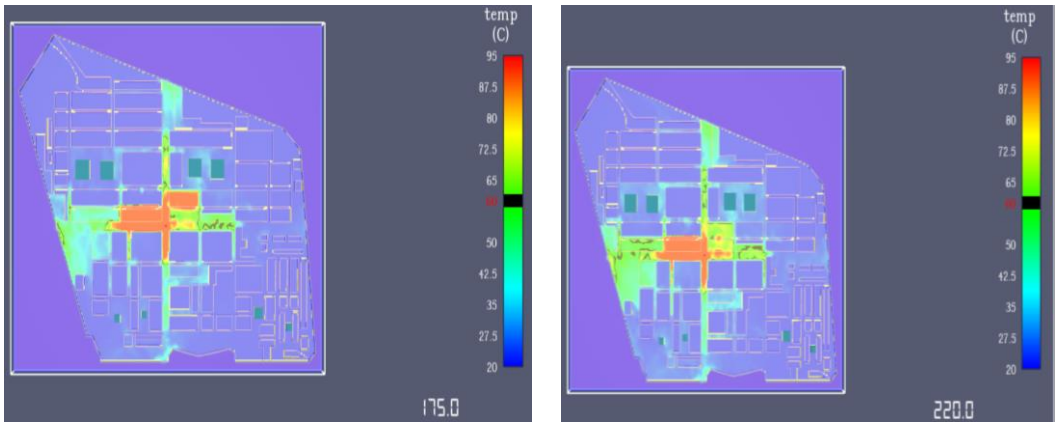
According to the smoke concentration detection slices in Fig. 3, at 58 s, visibility at Exit 2 and Exit 7 declined to less than 10 m, suggesting that timely response at the initial stage can greatly reduce visibility's effect on evacuation. At 63 s, visibility at Exit 9 rapidly dropped below 10 m. At 145 s, visibility in the main passage, Exit 4, and Exit 6 fell below 10 m, making safe evacuation impossible. At 330 s, visibility throughout the building dropped below 10 m.



a) Smoke visibility at 58 s b) Smoke visibility at 330 s

Figure 3: Simulation results of fire smoke visibility.

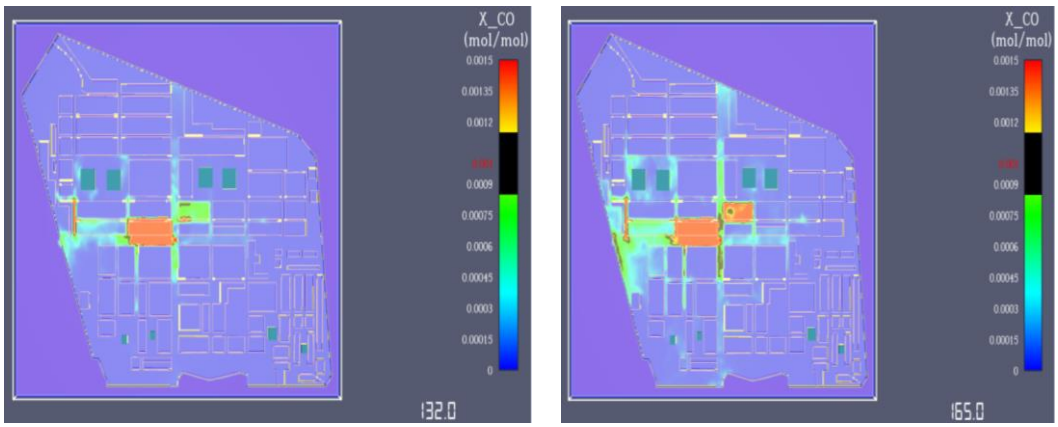
Smoke temperature simulation: According to the temperature detection slices in Fig. 4, high temperature radiated from the ignition point and increased over time. At 175 s, the temperature at Exit 9 reached the human body tolerance limit (60 °C). At 220 s, the temperature at Exit 9 exceeded 70 °C.



a) Temperature slice simulation at 175 s b) Temperature slice simulation at 220 s

Figure 4: Simulation results of fire scene temperature changes.

CO concentration simulation: From the slice diagram (Fig. 5) of CO concentration detection, CO had already diffused to the left main pathway at 132 s. At 165 s, the CO concentration at Exit 9 reached the critical value (0.1 %) and peaked at 0.15 % at 230 s.



a) Simulation of CO concentration at 132 s b) Simulation of CO concentration at 165 s

Figure 5: Simulation results of CO concentration changes.

In summary, the critical values of fire smoke temperature and CO concentration were reached earlier than the critical value of visibility. This indicates that smoke visibility had the greatest influence among smoke visibility, smoke temperature, and CO concentration. At 145 s, visibility at the nine exits declined to 10 meters, preventing non-evacuated personnel from finding the exit, leading to evacuation failure. Thus, the available safe evacuation time was determined to be t_{aset} = 145 s.

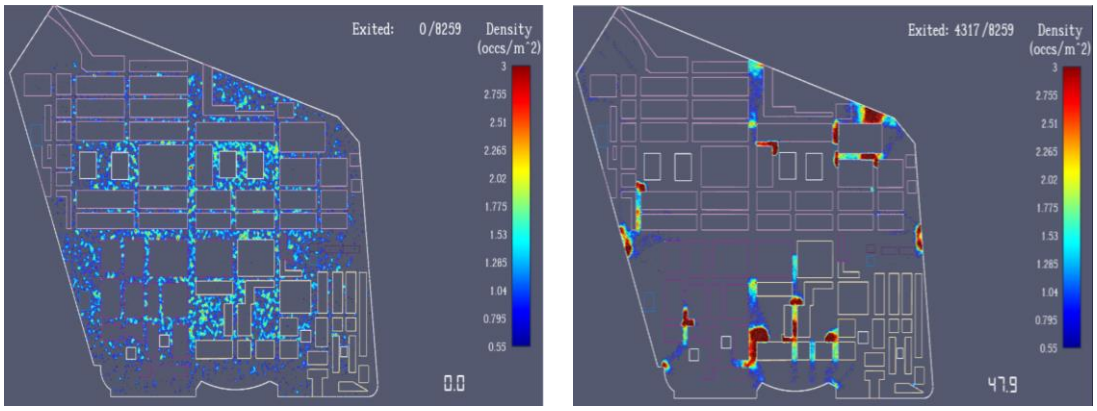
4.2 Pathfinder-based evacuation simulation results

In this simulation, 8,259 people on the first floor of Silk Clothing City needed evacuation. All evacuees utilized the nine safety exits, choosing the nearest exit. At 46 s, as shown in Fig. 6, more than half of the personnel were evacuated to safety through the exits, with 4,138 people already evacuated and no one remaining in any store. At 78.2 s, personnel near Exits 1 and 5 were completely evacuated, totalling 6,664 people. At 101.6 s, 7,636 people were evacuated, with the remaining 623 evacuating through Exits 2, 3, and 6. At 137.8 s, all 8,259 people were evacuated.

a) Evacuation simulation at 46 s b) Evacuation simulation at 137.8 s

Figure 6: Simulation results of evacuation in case of fire.

According to the crowd density diagram (Fig. 7), the crowd density in the building space was generally low, with a few areas reaching a density of 0.8 occs/m^2, mostly concentrated in the aisles between stores. The heat map of crowd flow density at 47.9 s of evacuation reveals a large red area in the aisle near the exit. This indicates a very high density of people in this area during the evacuation process, with densities reaching up to 3 occs/m^2. This high density led to serious congestion, greatly reducing the speed of evacuation and potentially causing stagnation.



a) Initial crowd density simulation b) Crowd density simulation at 47.9 s

Figure 7: Simulation results of crowd density to be evacuated.

The crowd evacuation route (Fig. 8) demonstrates that evacuees chose the nearest exit, with evacuation routes generally being the straight line distance between their position and the exit. Pathfinder's agent-based simulation allowed individuals to continuously recalibrate their movements based on current information to choose the nearest safety exit.

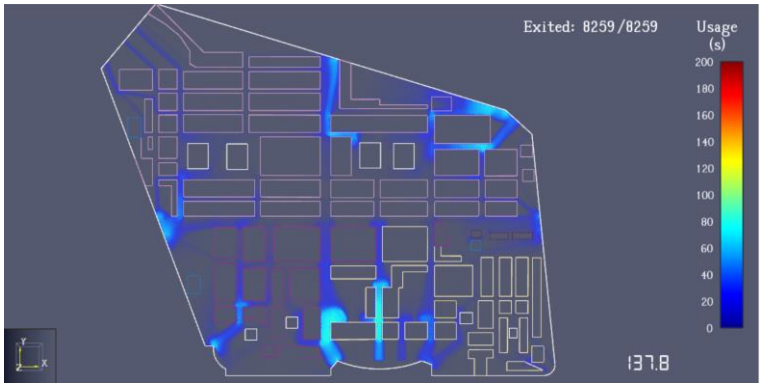


Figure 8: Crowd evacuation route diagram.

The evacuation move time was calculated as t_{move} = 137.8 s according to the Pathfinder simulation data. Including the fire detection alarm time t_{det} = 30 s and personnel response time t_{resp} = 30 s, the required safe evacuation time for personnel on the first floor of Silk Clothing City was t_{rest} = 137.8 s + 30 s + 30 s = 197.8 s. The available evacuation time simulated by PyroSim was t_{aest} = 145 s. According to the theory of safe evacuation, as the available safe evacuation time t_{aest} was greater than the required safe evacuation time t_{rest}, the safe evacuation conditions were not met.

4.3 Spatial layout optimization

Optimization scheme design: According to the PyroSim simulation results, smoke visibility had the greatest influence among smoke visibility, temperature, and CO concentration. Therefore, the effect of smoke visibility on the safe evacuation of personnel should be prioritized in the spatial layout optimization process for the study object. Without altering the original pattern much, the layout was optimized by incorporating smoke-proof walls and smoke exhaust pipes. This optimization was designed to effectively slow down the spread of smoke, rapidly expel smoke, reduce indoor smoke accumulation, improve evacuation efficiency in case of a severe fire, and further reduce the risk of fire spread. The optimized building model is shown in Fig. 9.

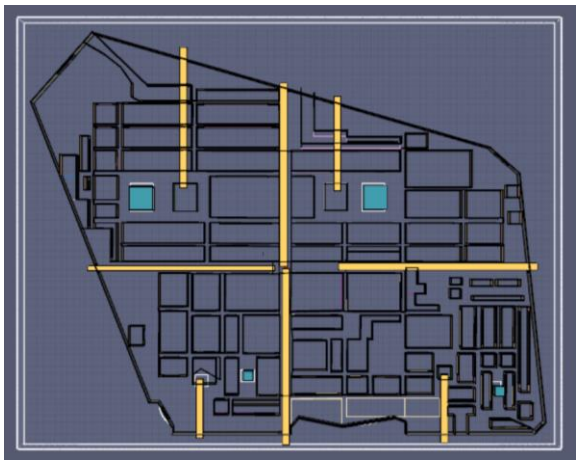
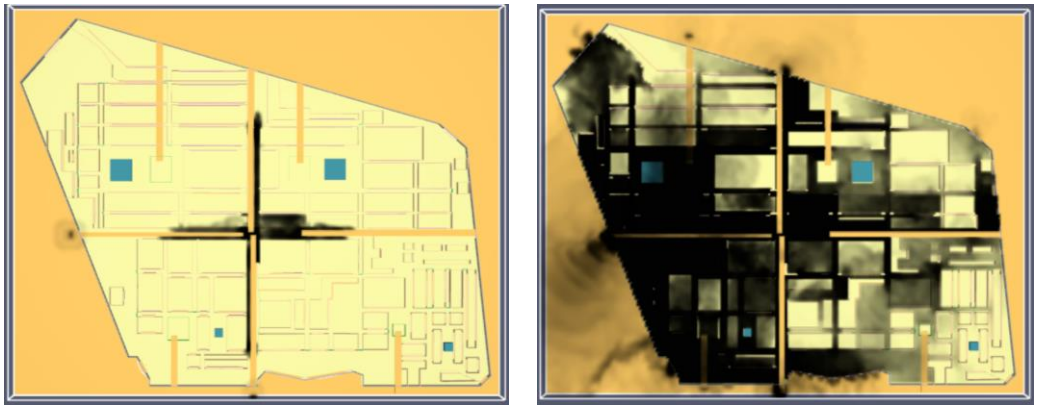


Figure 9: Spatial layout optimization model of the study object.

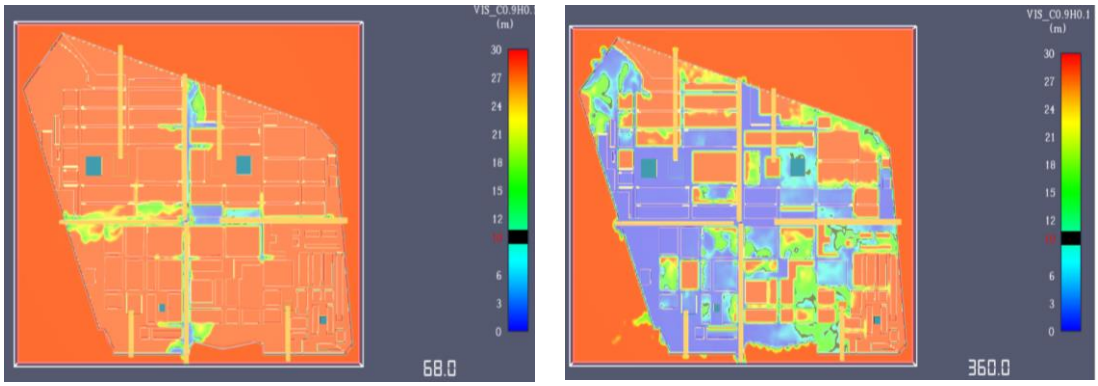
Simulation process of smoke spread: Fig. 10 illustrates the smoke spread process, showing the degree of smoke diffusion at 30 s, 90 s, 270 s, and 360 s. At 30 s, the smoke exhaust pipes had begun to discharge indoor smoke outside, with smoke mainly concentrated in the main pathway where concentration was high. By 90 s, the effects of smoke-proof walls and exhaust pipes were more apparent, reducing smoke concentration in the main pathway compared with before optimization. High smoke concentrations were now mainly near the fire source. At 270 s, the effects of the smoke-proof walls and exhaust pipes were less noticeable, and the main aisles were filled with thick smoke. By 360 s, when the simulation ended, the entire building was filled with thick smoke, which was spreading outward. Thus, the first 90 s of the fire showed remarkable effectiveness of the smoke-proof walls and exhaust pipes, and this period should be utilized fully for evacuating personnel to safety.



a) Simulation of fire smoke spread at 30 s b) Simulation of fire smoke spread at 360 s

Figure 10: Simulation of fire smoke spread process at various time intervals.

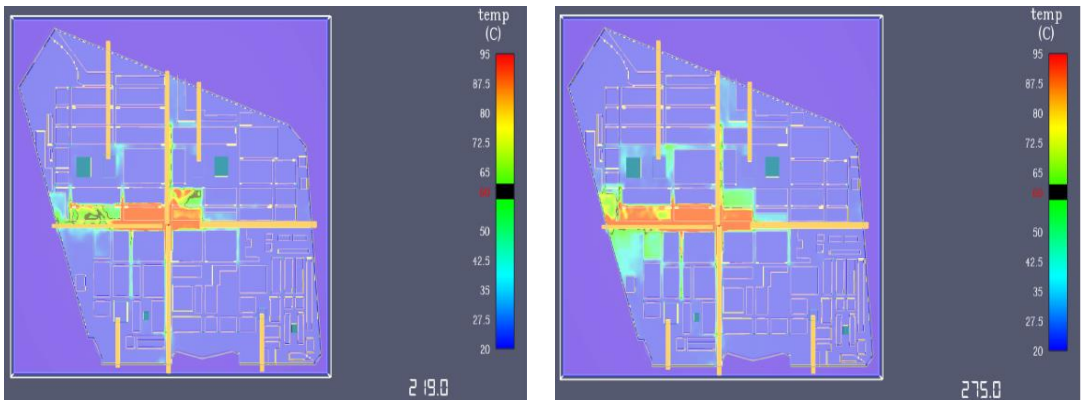
Smoke visibility analysis: According to the smoke concentration detection slice shown in Fig. 11, at 68 s, visibility at Exits 2 and 7 was less than 10 m. At 75 s, visibility at Exit 9 also dropped below 10 m. At 198 s, visibility in the main pathways had declined to below 10 m, making safe evacuation difficult at the six exits. At 360 s, when the simulation ended, visibility throughout the building had nearly dropped below 10 m. Compared with the situation before optimization, the time before visibility at all exits declined to 10 m was extended from 145 s to 205 s, adding 60 s to evacuation time and indicating remarkable effects of the smoke-proof walls and smoke discharge channels.



a) Simulation of fire smoke visibility at 68 s b) Simulation of fire smoke visibility at 360 s

Figure 11: Simulation of fire smoke visibility at various time intervals.

Smoke temperature analysis: According to the temperature detection slice in Fig. 12, the temperature at Exit 9 reached the tolerance limit of 60 °C at 219 s and approached 90 °C by 275 s.

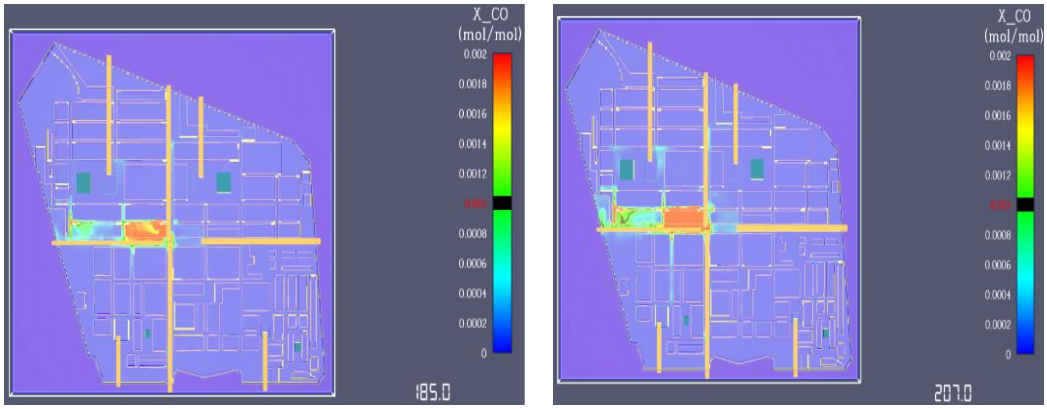


a) Fire smoke temperature slice at 219 s b) Fire smoke temperature slice at 275 s

Figure 12: Simulation of fire smoke temperature at various time intervals.

Combining these results with the temperature change curves at Exit 9, the evacuation function at Exit 9 failed at 219 s. Compared with the situation before optimization, the time before reaching the temperature limit at Exit 9 increased from 175 s to 219 s, demonstrating a clear optimization effect.

CO concentration analysis: From the CO concentration detection slice, as shown in Fig. 13, CO concentration increased with the spread of the fire from the ignition point to surrounding areas. At 185 s, the fire had spread to the left main pathway. At 207 s, CO concentration at Exit 9 on the left reached the risk value of 0.1 % and peaked at 0.35 % at 272 s. Compared with the situation before optimization, the time before reaching the CO concentration limit at Exit 9 increased from 165 s to 207 s, reflecting a notable optimization effect.



a) CO concentration at 185 s b) CO concentration at 207 s

Figure 13: Simulation of CO concentration at various time intervals.

Fig. 13 shows that, compared with visibility and smoke temperature, critical values for smoke temperature and CO concentration appeared later. The fire simulation results indicate that visibility had the greatest effect among these factors. At 205 s, visibility at the nine exits declined to 10 m, preventing non-evacuated personnel from finding the exits and leading to evacuation failure.

In summary, simulations of optimized smoke visibility, smoke temperature, and CO concentration indicated an available evacuation time, t_{rest}, of 205 s, as determined by PyroSim. According to the theory of safe evacuation, safe evacuation is feasible if the available safe evacuation time t_{aest} is greater than the required evacuation time t_{rest}. After optimizing the spatial layout, the fire risk in the shopping mall was significantly reduced. Specifically, the time for visibility at the exits to drop to 10 m increased from 145 s to 205 s, adding 60 s to evacuation time and greatly enhancing the probability of a successful escape.

5. CONCLUSION

This study analysed fire hazards and safe evacuation in large buildings by examining the effects of smoke spread, CO concentration, visibility, and temperature on evacuation safety using PyroSim. The *ASET* was determined, and the *REST* for personnel was analysed using Pathfinder. The large building – Silk Clothing City in Jiangsu Province, China – served as a case study. Based on simulation results, a layout optimization strategy was proposed to enhance evacuation efficiency. The key conclusions are:

(1) The fire in a large building was simulated using PyroSim. The results showed that at 145 s, visibility at the main pathway and Exits 4 and 6 fell below 10 m, compromising safe evacuation. By 175 s, the temperature at Exit 9 reached the 60 °C tolerance limit for humans. At 165 s, CO concentration at Exit 9 on the left side reached the risk value of 0.1 %. Among the three factors – smoke visibility, temperature, and CO concentration – visibility had the greatest influence.

(2) Pathfinder analysis revealed congestion in the aisles between west and east stores, affecting the final evacuation time. According to the theory of safe evacuation, the available evacuation time t_{aest} was shorter than the required safe evacuation time t_{rest}, leading to evacuation failure.

(3) The spatial layout of the building was optimized. To address issues identified in the evacuation simulation, smoke-proof walls and smoke exhaust pipes were added. The optimized model was then re-simulated. This simulation showed that the available safe evacuation time t_{aest} was longer than the required safe evacuation time t_{rest}, confirming successful evacuation.

In summary, PyroSim fire simulation software and Pathfinder evacuation simulation software effectively analyse fire risk and crowd evacuation efficiency in large, complex environments. They help identify bottlenecks in the evacuation process. By integrating spatial layout design for fire protection, safe and efficient evacuation strategies can be developed. This approach provides critical time for emergency management and safety in environments such as shopping malls and business districts.

The simulation model used in this study simplified fire scene types and lacked comprehensive data on crowd density, personnel characteristics, and social forces during evacuation. Future research should address these gaps to enhance the authenticity and reliability of the results. These areas represent important directions for follow-up research.

ACKNOWLEDGEMENT

The study was supported by the Applied Science Foundation Planning Project of Changzhou (Grant No. CJ20235029) and the Talent Introduction Project of Changzhou University (Grant No. ZMF23020082).

REFERENCES

[1] Zhong, W.; Yu, J. Y. (2023). Real-time fire evacuation system under smart city background, *China Safety Science Journal*, Vol. 33, No. 2, 179-184, doi:10.16265/j.cnki.issn1003-3033.2023.02.2798

[2] Ronchi, E.; Corbetta, A.; Galea, E. R.; Kinateder, M.; Kuligowski, E.; McGrath, D.; Pel, A.; Shiban, Y.; Thompson, P.; Toschi, F. (2019). New approaches to evacuation modelling for fire safety engineering applications, *Fire Safety Journal*, Vol. 106, 197-209, doi:10.1016/j.firesaf.2019.05.002

[3] Beverly, J. L.; Bothwell, P. (2011). Wildfire evacuations in Canada 1980-2007, *Natural Hazards*, Vol. 59, No. 1, 571-596, doi:10.1007/s11069-011-9777-9

[4] Suvar, M. C.; Kovacs, I.; Pasculescu, V. M.; Vlasin, N.-I.; Florea, G. D. (2019). Analysis of human behavior and evacuation in building fires using computer evacuation models, *Environmental Engineering and Management Journal*, Vol. 18, No. 4, 921-928, doi:10.30638/eemj.2019.089

[5] Ronchi, E. (2021). Developing and validating evacuation models for fire safety engineering, *Fire Safety Journal*, Vol. 120, Paper 103020, 8 pages, doi:10.1016/j.firesaf.2020.103020

[6] Lu, J. T.; Yang, N. D.; Ye, J. F.; Liu, X. G.; Mahmood, N. (2015). Connectionism strategy for industrial accident-oriented emergency decision-making: a simulation study based on PCS model, *International Journal of Simulation Modelling*, Vol. 14, No. 4, 633-646, doi:10.2507/IJSIMM14(4)6.315

[7] Tang, F.; Ren, A. (2012). GIS-based 3D evacuation simulation for indoor fire, *Building and Environment*, Vol. 49, 193-202, doi:10.1016/j.buildenv.2011.09.021

[8] Schmidt-Polonczyk, N.; Burtan, Z.; Liszka, P. (2021). Simulation of the evacuation of people in a road tunnel in the event of fire – case study, *Archives of Mining Sciences*, Vol. 66, No. 1, 13-28, doi:10.24425/ams.2021.136689

[9] Mossberg, A.; Nilsson, D.; Frantzich, H. (2022). Evaluating new evacuation systems related to human behaviour using a situational awareness approach – a study of the implementation of evacuation elevators in an underground facility, *Fire Safety Journal*, Vol. 134, Paper 103693, 10 pages, doi:10.1016/j.firesaf.2022.103693

[10] Gwynne, S. M. V.; Kuligowski, E. D.; Kinsey, M. J.; Hulse, L. M. (2017). Modelling and influencing human behaviour in fire, *Fire and Materials*, Vol. 41, No. 5, 412-430, doi:10.1002/fam.2391

[11] Gerges, M.; Demian, P.; Adamu, Z. (2021). Customising evacuation instructions for high-rise residential occupants to expedite fire egress: results from agent-based simulation, *Fire*, Vol. 4, No. 2, Paper 21, 18 pages, doi:10.3390/fire4020021

[12] Król, A.; Król, M. (2020). The factors determining the number of the endangered people in a case of fire in a road tunnel, *Fire Safety Journal*, Vol. 111, Paper 102942, 13 pages, doi:10.1016/j.firesaf.2019.102942

[13] Mirahadi, F.; McCabe, B.; Shahi, A. (2019). IFC-centric performance-based evaluation of building evacuations using fire dynamics simulation and agent-based modeling, *Automation in Construction*, Vol. 101, 1-16, doi:10.1016/j.autcon.2019.01.007

[14] Qin, J.; Liu, C.; Huang, Q. (2020). Simulation on fire emergency evacuation in special subway station based on Pathfinder, *Case Studies in Thermal Engineering*, Vol. 21, Paper 100677, 7 pages, doi:10.1016/j.csite.2020.100677

[15] Yuan, C. Y.; Li, M. Q.; Gu, Y. P.; Wei, Y. P.; Chai, G. Y. (2022). Structural equation model analysis on self-efficacy and fire behavior of shopping mall staff, *Journal of Safety Science and Technology*, Vol. 18, No. 9, 174-180

[16] Yuan, D. S.; Lu, X. T.; Zhong, F. P. (2020). Fire simulation and evacuation plan for old emporium based on FDS, *Journal of Hunan University of Science & Technology (Natural Science Edition)*, Vol. 35, No. 4, 25-31, doi:10.13582/j.cnki.1672-9102.2020.04.004

[17] Wang, N.; Gao, Y.; Li, C.-Y.; Gai, W.-M. (2021). Integrated agent-based simulation and evacuation risk-assessment model for underground building fire: a case study, *Journal of Building Engineering*, Vol. 40, Paper 102609, 13 pages, doi:10.1016/j.jobe.2021.102609

[18] Yen, H.-H.; Lin, C.-H.; Tsao, H.-W. (2021). Time-aware and temperature-aware fire evacuation path algorithm in IoT-enabled multi-story multi-exit buildings, *Sensors*, Vol. 21, No. 1, Paper 111, 24 pages, doi:10.3390/s21010111

[19] Krasuski, A.; Krenski, K. (2019). A-evac: the evacuation simulator for stochastic environment, *Fire Technology*, Vol. 55, No. 5, 1707-1732, doi:10.1007/s10694-019-00827-7

[20] Shoshe, M. A. M. S.; Rahman, M. A. (2022). Improvement of heat and smoke confinement using air curtains in informal shopping malls, *Journal of Building Engineering*, Vol. 46, Paper 103676, 22 pages, doi:10.1016/j.jobe.2021.103676

[21] Liang, B.; van der Wal, C. N.; Xie, K.; Chen, Y.; Brazier, F. M. T.; Dulebenets, M. A.; Liu, Z. (2023). Mapping the knowledge domain of soft computing applications for emergency evacuation studies: a scient metric analysis and critical review, *Safety Science*, Vol. 158, Paper 105955, 18 pages, doi:10.1016/j.ssci.2022.105955

[22] Menzemer, L. W.; Ronchi, E.; van Karsten, M. M.; Gwynne, S.; Frederiksen, J. (2023). A scoping review and bibliometric analysis of methods for fire evacuation training in buildings, *Fire Safety Journal*, Vol. 136, Paper 103742, 19 pages, doi:10.1016/j.firesaf.2023.103742

[23] Guo, X. Y.; Zeng, Z.; Li, M. X.; Fu, S. (2022). Simulation of aircraft cabin evacuation strategy based on exit flow equilibrium, *International Journal of Simulation Modelling*, Vol. 21, No. 2, 261-272, doi:10.2507/IJSIMM21-2-601