Int j simul model 24 (2025) 3, 461-472
Original scientific paper

SIMULATION OF EMERGENCY EVACUATION IN DENSE-OCCUPANCY HIGH-RISE BUILDINGS

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Abstract
To enhance the efficiency of emergency evacuation in high-rise buildings and formulate scientifically sound evacuation strategies, five strategies were designed in this study: no-command evacuation, downward evacuation, nearest refuge floor evacuation, speed-priority evacuation, and elevator-assisted evacuation, based on crowd evacuation dynamics theory. Using Pathfinder simulation software, the evacuation times associated with these strategies were compared, taking a typical 37-story residential building layout as an example. The strategy yielding the shortest evacuation time was identified. Results show that under the no-command evacuation scenario, the evacuation time was 248.8 seconds. Implementation of the nearest refuge floor strategy reduced the time to 232.0 seconds, a decrease of 6.7 %. With the speed-priority strategy, the evacuation time was further shortened to 215.8 seconds. When elevator-assisted evacuation was employed, the evacuation time decreased markedly to 193 seconds. These findings offer decision support and a theoretical reference for the development of emergency evacuation plans and the conduct of evacuation drills in high-rise buildings.
(Received in June 2025, accepted in August 2025. This paper was with the authors 2 weeks for 2 revisions.)

Key Words: High-Rise Buildings, Emergency Evacuation, Pathfinder Simulation, Evacuation Strategy Comparison

1. INTRODUCTION

With the acceleration of urbanization, high-rise buildings have become an essential component of modern cities. In China alone, the annual growth rate of high-rise buildings is approximately 10 %, making them an important means of urban spatial expansion and land conservation [1]. However, with the continuous increase of high-rise buildings, the issue of crowd evacuation during emergencies has become one of the key factors affecting building safety [2]. Although modern designs incorporate various safety technologies and facilities, efficiently evacuating personnel within a limited time during emergencies, such as fires, earthquakes, and floods, remains a major challenge for safeguarding lives and improving building safety. High population density and limited evacuation routes often reduce the efficiency of crowd evacuation in emergency situations, exacerbating the risks associated with emergency evacuation and refuge [3]. Therefore, the scientific design of emergency evacuation strategies for high-rise buildings, aimed at reducing evacuation time, preventing crowd congestion, and minimizing safety risks, has become a key study direction in building safety.

Many countries and regions have developed relevant regulations and standards for emergency evacuation in high-rise buildings. For example, the "Building Design Fire Safety Code" of the People's Republic of China stipulates that, in the event of an emergency, such as a fire, the evacuation time must remain within a reasonable range to ensure the safe evacuation of occupants [4]. A series of related laws and standards increasingly demand high evacuation efficiency. Therefore, scientifically formulated emergency evacuation strategies for high-rise buildings are fundamental for improving evacuation efficiency and ensuring the safety of occupants. However, existing studies have mainly focused on the macro-level construction of evacuation theories and models. Further exploration is needed on fine-grained simulation modelling and validation of emergency strategies in specific building environments [5]. Additionally, high-rise buildings often face challenges in traditional evacuation drills because of their long vertical evacuation distances, complex occupant behaviours, and limited evacuation spaces. These drills not only require considerable human and material resources but also may pose safety risks during large-scale evacuation exercises. Furthermore, their effectiveness can be easily influenced by factors such as participants' attitudes, management execution, and skill levels, making it difficult to accurately reflect actual evacuation scenarios during emergencies. To overcome these limitations, this study uses simulation technology to design evacuation scenarios for high-rise buildings, compares evacuation efficiency under different strategies, and analyses the spatiotemporal characteristics of personnel movement during high-rise building evacuations. The study proposes an optimal strategy for improving evacuation efficiency during emergencies in high-rise buildings.

2. STATE OF THE ART

From the perspective of study content, most studies on emergency evacuation during unexpected events focus on low-rise buildings, such as teaching buildings, office buildings, and shopping malls, which typically have shorter vertical evacuation distances and relatively simple evacuation paths. For example, Del Zoppo et al. [6] investigated the impact of different exit designs on evacuation efficiency in low-rise buildings. They found that the number and distribution of exits significantly influence evacuation time. Shi et al. [7] simulated the evacuation process in commercial buildings, analysed occupant behaviour patterns under different emergency scenarios, and proposed adaptive evacuation strategies. Peacock et al. [8] further explored the dynamic characteristics of personnel movement during evacuations in office and commercial buildings and proposed optimized evacuation path design strategies. These studies provide the theoretical foundation for emergency evacuation strategies in low-rise buildings. Although some studies have started to focus on emergency evacuation in high-rise buildings, most studies still concentrate on analysing individual strategies, such as stairs, elevators, or refuge floors. For example, Wu et al. [9] studied the application of elevator-assisted evacuation in high-rise buildings, exploring how elevators can help reduce evacuation time. Yan et al. [10] analysed the effectiveness of using refuge floors, concluding that they can effectively alleviate evacuation pressure in high-rise buildings. The study at this stage primarily focuses on a micro-level perspective, analysing the relationship between avoidance behaviour and evacuation efficiency based on pedestrian movement patterns. However, few studies have addressed the synergy of multiple strategies, and the coordination and optimization between them lacks in-depth exploration. In high-rise building environments, the complexity of vertical evacuation paths, the flow of personnel across multiple floors, and the synergy between various evacuation measures require efficient, flexible, and comprehensive emergency evacuation strategies. Therefore, designing and implementing multi-strategy coordinated evacuation plans remains an important issue in current study.

Regarding simulation analysis methods for high-rise building emergency evacuation, existing study primarily focuses on evacuation path selection, planning, and optimization. Most scholars concentrate on local guidance to change personnel behaviour, thereby influencing the evacuation process. For example, Neto et al. [11] proposed a fire simulation-based evacuation model to analyse the impact of different evacuation paths and exit configurations on evacuation efficiency in high-rise buildings. Norazahar et al. [12] developed a dynamic evacuation simulation model and optimized the use of stairs and elevators to assess the effect of different evacuation paths on evacuation time in high-rise buildings. Zhang et al. [13] proposed a dynamic evacuation simulation model based on flow distribution, focusing on the dynamic characteristics of personnel movement between multiple floors in high-rise buildings. They found that reasonable flow distribution can significantly improve evacuation efficiency and reduce evacuation bottlenecks caused by crowd concentration. Rico et al. [14] constructed a multi-factor coupled evacuation simulation model, which considers personnel response times, behaviour patterns, and evacuation path selection. They then proposed a multi-dimensional evacuation optimization strategy and analysed the interaction between personnel behaviour and evacuation channels in high-rise buildings. Han et al. [15] put forward an individual evacuation behaviour-based simulation model, which simulates evacuation processes under different scenarios. They found that the emotions, judgment, and surrounding environment of individuals greatly influence evacuation efficiency. They then analysed the impact of individual and group behaviour patterns on the evacuation process. In sum, current study mainly focuses on local path optimization and individual behaviour simulation, with few studies considering how to dynamically plan and organize large-scale evacuation groups in high-rise buildings from a global perspective. Moreover, although existing studies offer individual and localized optimization solutions, they lack global coordination between multiple evacuation paths, personnel behaviour, and environmental factors in high-rise buildings. In actual large-scale evacuations, reasonably coordinating different measures, optimizing flow distribution, and dynamically guiding evacuation groups remain key challenges in studies on emergency evacuation for high-rise buildings.

To address the shortcomings of existing study, this study proposes an optimization plan for coordinating multiple evacuation measures based on reasonable flow distribution across different evacuation exits, combined with building spatial layout and personnel density. This study also proposes dynamic evacuation strategies based on simulation, optimizing the coordinated use of stairs, elevators, and refuge floors and analysing the behaviour patterns of large-scale evacuation groups in the complex environment of high-rise buildings. Using Pathfinder software, the evacuation process in high-rise buildings is simulated to evaluate the evacuation efficiency and time performance of different evacuation strategies in emergency situations. The aim is to provide decision support and theoretical basis for improving emergency evacuation efficiency during incidents in high-rise buildings.

The remainder of this study is organized as follows: Section 3 describes the scenarios and parameter setting rules for the simulation of emergency evacuation in high-rise buildings. Section 4 compares the simulation results of various evacuation strategies and analyses their evacuation efficiency. The final section summarizes the study and presents relevant conclusions.

3. METHODOLOGY

3.1 Crowd evacuation dynamics theory

Crowd evacuation dynamics is a theoretical framework based on individual movement patterns and group interaction mechanisms, analysing the spatial migration of individuals under emergency conditions. This theory seeks to reveal the interaction mechanisms between individuals, their environment, and other individuals, and it uses quantitative modelling methods to characterize the behavioural evolution features during evacuation [16]. Pathfinder employs an agent-based modelling approach, enabling the precise simulation of each individual's behavioural choices, path selection, and decision-making process during evacuation. The software incorporates multiple movement models to simulate the dynamic behaviour of individuals during evacuation, including the social force pedestrian flow and steering movement models. Individual movement during evacuation is calculated primarily based on the following formulas [17]:

$$V_0 = \begin{cases} V_{max} = \dfrac{k - 0.266KD}{1.19} \ (D < 0.55) \\ V_{max} = \dfrac{k}{1.4} \ (D \geq 0.55) \end{cases} \tag{1}$$

In these equations, V_0 represents the initial speed at the starting position (in m/s), V_{max} is the maximum speed (in m/s), K is the evacuation speed influencing factor, and D is the crowd density inside the building (in people/m²). The formula to calculate the initial acceleration of individuals in the crowd is given by:

$$a_{max} = \frac{V_{max}}{t_{accel}} \tag{2}$$

where a_{max} is the maximum acceleration (in m/s²), and t_{accel} is the acceleration time (in seconds). The formula to determine the evacuation direction is as follows:

$$C_{seek}\frac{\theta_t}{2\pi} \tag{3}$$

where C_{seek} is the weight value of each movement direction, and the direction with the smallest weight is chosen as the evacuation direction for the individual in the crowd. θ_t represents the angle between the velocity direction and the tangent of the optimal evacuation curve within the software. The velocity at the destination position is calculated as the following position vector:

$$|\overrightarrow{V_2}| = \overrightarrow{V_1} + \overrightarrow{a_1}\,\Delta t \tag{4}$$

$$|\overrightarrow{\rho_2}| = \overrightarrow{\rho_1} + \overrightarrow{v_1}\,\Delta t \tag{5}$$

where $\overrightarrow{V_2}$ is the velocity at the destination, $\vec{\rho}$ is the current position vector, and Δt is the computation time step (in seconds). These steps constitute the basic procedure for evacuation simulation. After completing these steps, the system calculates the position reached by each individual. If an individual reaches the predetermined location, the calculation stops. If the individual has not reached the designated evacuation exit, the system will repeat the calculation until all individuals have evacuated.

3.2 Simulation scenarios and spatial parameter settings

A 37-story residential building is used as a case study to investigate evacuation strategies. The total height of the building is 111 meters, with a floor height of 3 meters, and the first floor is an empty lobby. The total floor plan measures 32 meters by 30 meters, designed with one elevator and four units per floor. Four units are set per floor, with different layouts for larger and smaller apartments. The larger units accommodate five to six people, whereas the smaller units accommodate four to five people. According to the "Code for the Design of Refuge Floors in High-Rise Civil Buildings" (GB 51143-2015) [17], the height of the refuge floor in high-rise buildings and the height difference between refuge floors should not exceed 50 meters. This building has refuge floors located on the 13th and 27th floors. The 3D model of the building is shown in Fig. 1.

The four residential units are distributed around the building, with the central area consisting of public spaces including stairwells, elevator shafts, and corridors. The apartments comprise a living room, three to four bedrooms, a bathroom, a kitchen, a balcony, and a study room. The building is equipped with one elevator and two staircases. The elevator has a capacity of 21 people, an acceleration of 1.2 m/s², a maximum speed of 2.5 m/s, and a door opening time of 7 seconds. The stairwell is 1.2 meters wide and 2.5 meters long. The total area of the refuge floor is 259 square meters, which can accommodate approximately 500 people for temporary shelter. Fig. 2 illustrate the standard floor plan layout.

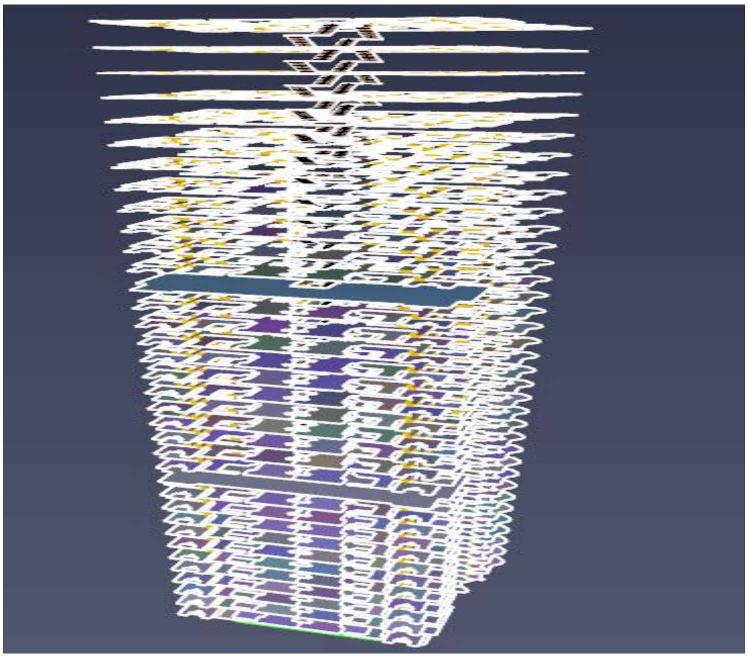


Figure 1: 3D model of the building.

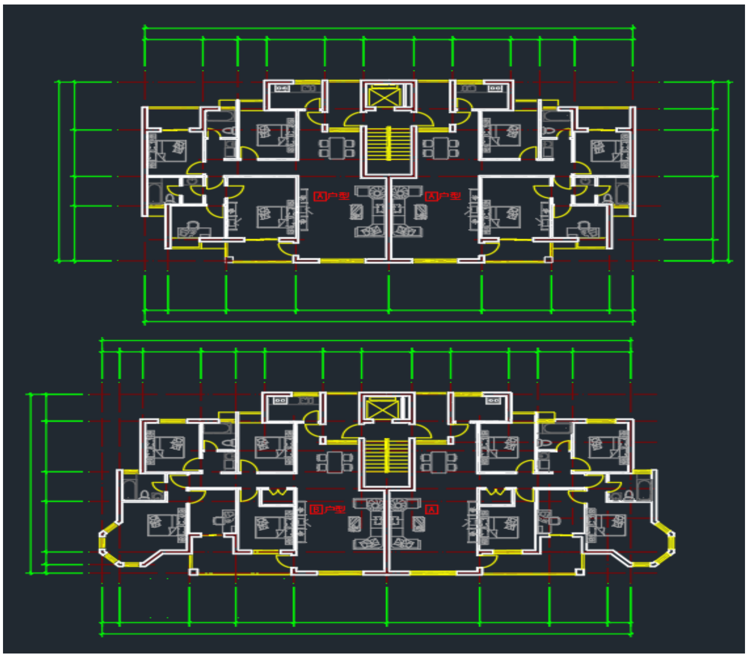


Figure 2: Floor plan.

3.3 Crowd evacuation parameter settings

(1) Personnel distribution: This study divides the population into three groups on the basis of the distribution of family members: children, adults, and the elderly. There are 234 children, 288 adults, and 280 elderly people. Each household is configured with one to two children, two adults, and zero to two elderly members, and the individuals are randomly distributed within the apartments to ensure the general applicability of the results.

(2) Personnel characteristic parameters: The characteristics of personnel include their physical fitness and mobility, which directly influence their movement speed and space occupation during evacuation. The physical and mobility parameters follow a normal distribution [10]. Tables I and II provide the specific parameters.

Table I: Physical parameters of personnel.

Personnel height				
Population	Maximum value	Minimum value	Average value	Variance
Children	1.70 m	1.12 m	1.39 m	0.05 m
Adult male	1.86 m	1.60 m	1.73 m	0.07 m
Adult female	1.69 m	1.47 m	1.58 m	0.06 m
Elderly men	1.82 m	1.58 m	1.70 m	0.06 m
Elderly female	1.65 m	1.45 m	1.55 m	0.05 m
Shoulder width of personnel				
Population	Maximum value	Minimum value	Average value	Variance
Children	38.0 cm	28.0 cm	36.0 cm	1.4 cm
Adult male	41.5 cm	33.5 cm	37.5 cm	2.0 cm
Adult female	38.7 cm	31.5 cm	35.1 cm	1.8 cm
Elderly men	40.0 cm	32.0 cm	36.0 cm	2.0 cm
Elderly female	37.6 cm	30.4 cm	34.0 cm	1.8 cm

Table II: Personnel exercise capacity reference.

Population	**Maximum value**	**Minimum value**	**Average value**	**Variance**
Children	2.00 m/s	1.19 m/s	1.61 m/s	0.22 m/s
Adult male	2.50 m/s	1.47 m/s	2.02 m/s	0.28 m/s
Adult female	2.44 m/s	1.33 m/s	1.88 m/s	0.25 m/s
Elderly men	1.33 m/s	0.49 m/s	0.91 m/s	0.11 m/s
Elderly female	1.19 m/s	0.36 m/s	0.77 m/s	0.08 m/s

(3) Personnel behaviour settings: Personnel behaviour dictates individual decision-making and action patterns during evacuation, including path selection, avoidance behaviour, and escape goals. Additionally, the evacuation follows a "first-come, first-served" principle, which can cause conflicts between slower-moving and faster-moving groups, leading to congestion. Therefore, the study adjusts the priority of the crowd to alleviate these issues.

(4) Spatial model parameters: In constructing the spatial model of the high-rise building, the total building height is 111 meters, and the standard floor height is 3 meters. The building's floor plan is approximately 32 meters by 30 meters, with elevator dimensions of 3 meters by 3 meters, corridor width of 1.7 meters, and stairwell width of 1.2 meters. The building's main entrance is 7 meters wide, the residential entrance is 1 meter wide, and the internal doors of the apartments are 0.8 meters wide.

3.4 Evacuation strategy design

This study uses Pathfinder simulation software to simulate evacuation under different strategies. It covers five main strategies: no-interference evacuation, downward evacuation, nearest refuge floor strategy, speed-priority evacuation, and elevator-assisted evacuation strategies [18]. By analysing and comparing these strategies, their evacuation efficiency and application effects during emergency evacuations in high-rise buildings are evaluated.

(1) Strategy 1: No-Interference Evacuation Strategy: Individuals are free to choose their evacuation path without intervention, automatically proceeding to the nearest exit or refuge floor. The evacuation ends when all individuals reach the exit or refuge floor. This strategy aims to determine the maximum evacuation time required without any planned evacuation strategy, reflecting the optimization of high-rise building emergency evacuation after strategic planning.

(2) Strategy 2: Individuals above the 13th floor (13th to 26th floors) evacuate to the refuge floor on the 13th floor, whereas individuals above the 27th floor (27th to 37th floors) evacuate to the refuge floor on the 27th floor. Individuals on the 1st to 12th floors directly evacuate to the ground. Fig. 3 shows the evacuation path planning for this strategy.

Figure 3: Personnel path planning for downward evacuation strategy.

(3) Strategy 3: Individuals on the 1st to 7th floors evacuate directly to the nearest exit. Individuals on the 8th to 20th floors evacuate to the refuge floor on the 13th floor, and individuals on the 21st to 37th floors evacuate to the refuge floor on the 27th floor. Fig. 4 illustrates the personnel path planning.

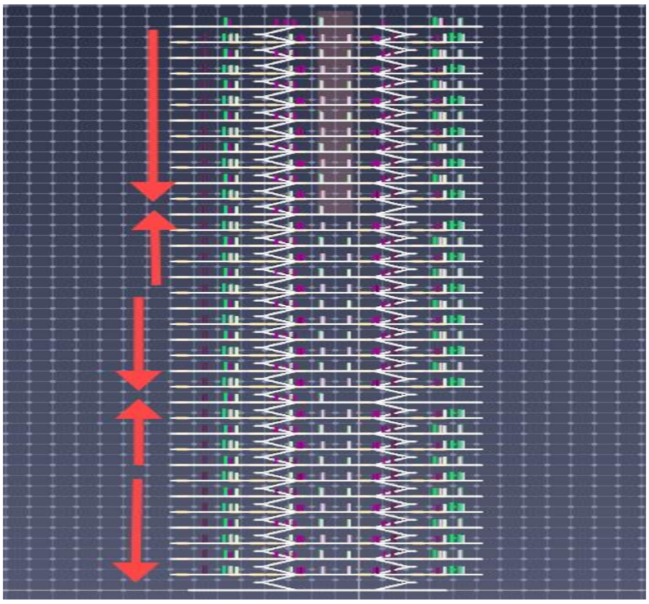


Figure 4: Personnel path planning for the nearest refuge floor strategy.

(4) Strategy 4: Speed-Priority Evacuation Strategy: This strategy allows faster-moving individuals to pass through evacuation points (such as stairway entrances or corners) first, while slower individuals (such as the elderly and children) temporarily wait until the evacuation path clears. However, the speed-priority strategy may increase the waiting time for certain groups,

especially for slower-moving individuals. Therefore, balancing and adjusting according to the characteristics of different groups is essential in practical applications. The personnel path planning is the same as in Strategy 3.

(5) Strategy 5: Elevator-Assisted Evacuation Strategy: The elevator-assisted evacuation strategy verifies the effectiveness of elevator-assisted evacuation in high-rise buildings through simulation methods. According to Zhian et al. [19], using elevators to assist in evacuation can significantly reduce evacuation time and help ensure the safety of personnel in high-rise buildings. Particularly, when the refuge floor on the 27th floor needs to accommodate more residents from upper floors, using elevators can significantly improve the evacuation efficiency for top-floor residents. This strategy allows residents above the 27th floor to evacuate to the refuge floor using elevators, while residents on other floors continue to use the stairs, further reducing stairwell congestion.

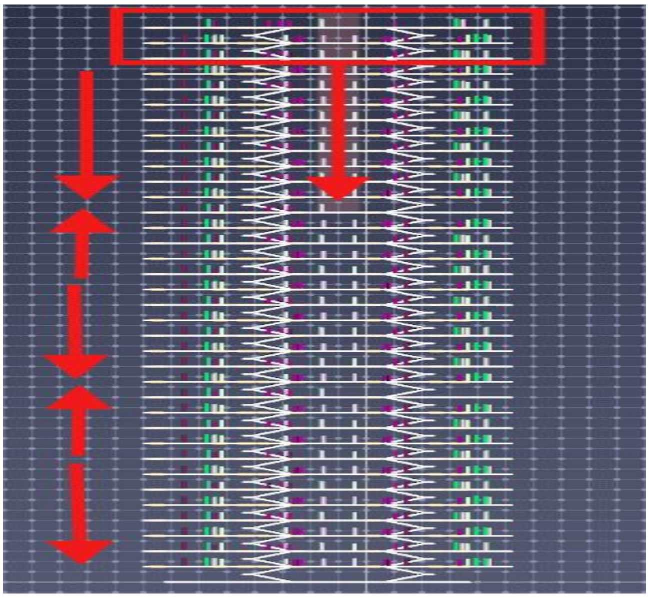


Figure 5: Personnel path planning for elevator-assisted evacuation strategy.

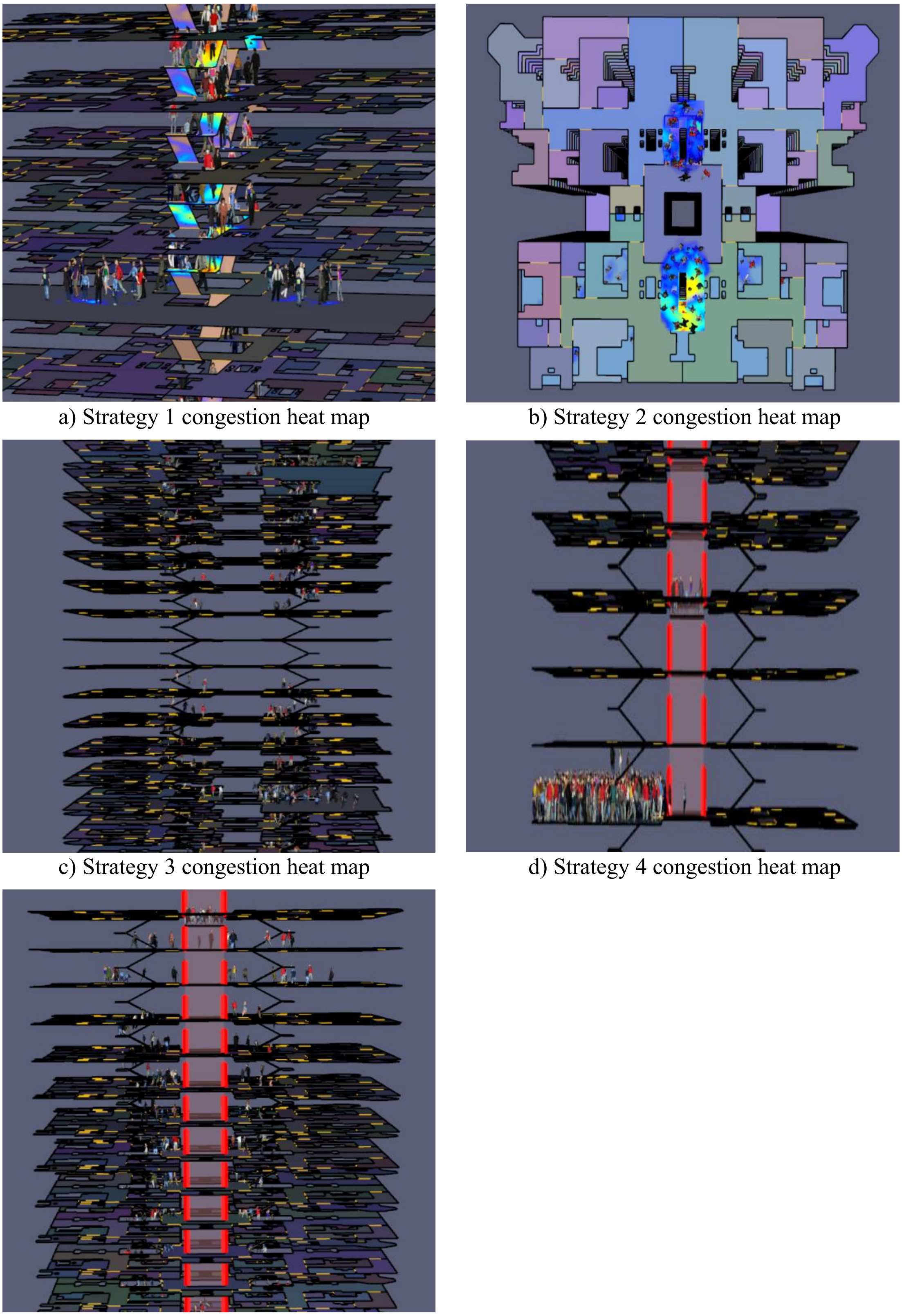
4. RESULT ANALYSIS AND DISCUSSION

4.1 Simulation results and analysis

This study utilizes Pathfinder simulation software to validate the evacuation processes of the five evacuation strategies designed in the previous section. It then analyses and compares the evacuation effects. Table III compares the total evacuation time for each strategy, and Figs. 6 a to 6 e depict the heatmaps for the five evacuation strategies.

Table III: Comparison of the total evacuation time of the five evacuation strategies.

Strategy	**Total evacuation time** (seconds)	**Reduce the time** (in seconds) **compared with the previous strategy**	**Reduce the proportion** (%) **compared with the previous strategy**	**The proportion of reduction compared to Strategy 1** (%)
Strategy 1	248.8	-	-	
Strategy 2	248.8	0	0	0
Strategy 3	232.0	16.8	6.7	6.7
Strategy 4	215.8	16.2	6.9	13.2
Strategy 5	193	22.8	10.5	22.4



a) Strategy 1 congestion heat map

b) Strategy 2 congestion heat map

c) Strategy 3 congestion heat map

d) Strategy 4 congestion heat map

e) Strategy 5 congestion heat map

Figure 6: Heat maps of five evacuation strategies.

The results in Table III and Fig. 6 reveal that the total evacuation time of Strategy 1, the no-interference evacuation strategy, is 248.8 seconds. Personnel on the lower floors predominantly head toward the exit on the first floor. Owing to the greater number of floors (1–12) and the longer distance to the exit, the evacuation time for these floors is longer. For the personnel on floors 13 to 37, they randomly choose to evacuate to either the 13th or 27th refuge floors, resulting in underutilization of stairway. The evacuation results of Strategy 2 are similar to those of Strategy 1. The evacuation time for lower-floor personnel is still longer because of the large number of floors. Congestion in the stairwells is also considerable, forming a noticeable “bottleneck effect”. However, Strategy 2 resolves the issue of reverse-direction evacuation, significantly reducing evacuation time for personnel on middle and upper floors.

The evacuation time of Strategy 3 is reduced by 16.8 seconds, a decrease of 6.7 % compared with Strategy 2. The evacuation time for exits and the 13th floor refuge is significantly reduced, but that for the 27th floor refuge remains largely unchanged. By setting up multiple refuge floors, the evacuation is evenly distributed, and congestion in stairwells on lower floors is effectively avoided. On the basis of Strategy 3, Strategy 4 introduces priority settings, requiring personnel to evacuate in the order of adult men, adult women, children, elderly men, and elderly women at congestion points to prevent slower-moving individuals from obstructing faster-moving ones. Compared with Strategy 3, Strategy 4 reduces the evacuation time by 16.2 seconds, a 6.9 % decrease. This strategy significantly improves the passage efficiency for top-floor residents in stairwells and alleviates the long-lasting congestion in the stairwells. Compared with that of Strategy 4, the evacuation time of Strategy 5 is reduced by 22.8 seconds, a 10.5 % reduction. Elevator-assisted evacuation significantly shortens the evacuation time for top-floor residents and reduces the pressure on stairwells. The escape rate for top-floor residents is greatly improved with the use of elevators to assist evacuation. Fig. 7 illustrates the total evacuation times for the five strategies.

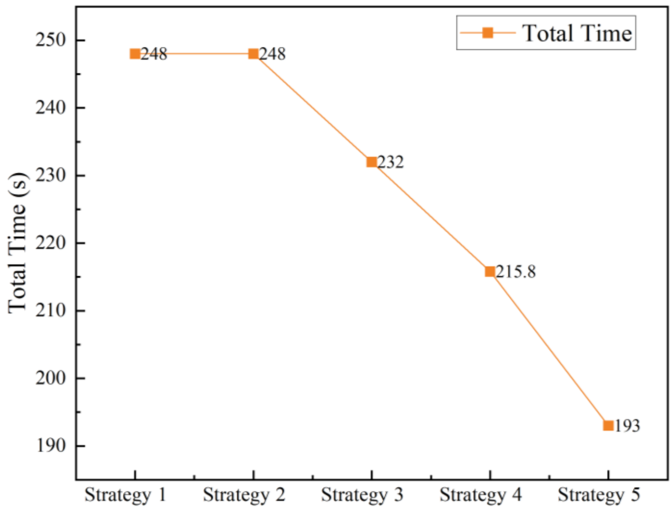


Figure 7: Comparison chart of total evacuation times for the five strategies.

The total evacuation time for the five strategies shows a decreasing trend, with Strategy 5 showing the most significant improvement, reducing evacuation time by 10.5 % compared with Strategy 4. The improvements between Strategy 3 and Strategy 2 and between Strategy 4 and Strategy 3 are similar, showing noticeable enhancements. However, the implementation difficulty of each strategy increases incrementally. Strategy 5 is the most challenging because it requires cooperation from evacuees, a high level of organization, compliance with elevator design standards, professional operators, and a complete management system. In practical applications, the appropriate evacuation strategy should be selected based on factors such as building characteristics, management level, and economic conditions. For typical high-rise buildings, Strategy 2 may be a suitable choice because it significantly improves evacuation efficiency while maintaining a relatively low implementation difficulty. For super-tall buildings, Strategy 4 may be more applicable. Although its implementation is complex, it can significantly reduce evacuation time and improve overall evacuation efficiency.

5. CONCLUSION

This study utilized Pathfinder simulation software to validate and compare different evacuation strategies derived from crowd evacuation dynamics theory. Flow distribution and path optimization theories were applied to simulate five distinct evacuation strategies. The evacuation time and efficiency of each strategy were assessed to evaluate their impact on the overall evacuation process. The following conclusions were drawn:

(1) To address the issue of emergency evacuation in high-rise buildings, a 3D model of a 37-story residential building was constructed using Pathfinder simulation software, and five different evacuation strategies were designed. The results show that optimizing evacuation paths, reasonably configuring refuge floors, and introducing elevator-assisted evacuation strategies can significantly improve evacuation efficiency and reduce evacuation time. These simulation results provide theoretical foundations and practical references for the development of evacuation plans for high-rise buildings.

(2) This study simulated five evacuation strategies. The simulation results demonstrate that Strategy 5 performs the best, reducing total evacuation time by 10.5 %. Strategy 4 reduces evacuation time by 6.9 % compared with Strategy 3. The effectiveness of each strategy depends on the specific design of the building and the ease of implementation. Selecting the appropriate strategy is crucial for improving the efficiency of emergency evacuation in high-rise buildings.

(3) For typical high-rise buildings, the nearest exit strategy provides a good balance between evacuation efficiency and implementation difficulty. However, for super-tall buildings, although the elevator-assisted evacuation strategy is more challenging to implement, it significantly improves evacuation efficiency, especially for top-floor residents. Theoretically, this study not only provides specific evacuation strategies for high-rise buildings but also offers theoretical support for optimizing evacuation through the synergy of multiple strategies. It lays a foundation for future study on building emergency management and evacuation strategies.

Through simulation, this study validates the effectiveness of evacuation strategies, refuge floor configuration, and personnel priority planning for enhancing evacuation efficiency in high-rise buildings. However, this study does not consider the impact of irrational behaviour on evacuation efficiency during emergencies. Future work can incorporate models of irrational individuals for realistic simulations. With the development of new technologies and management measures, future studies should also explore innovative evacuation strategies to further improve the efficiency of emergency evacuation in high-rise buildings.

ACKNOWLEDGEMENT

The study was supported by the Doctoral Research Start-up Project of North China University of Water Resources and Electric Power, the Science and Technology Planning Project of Henan Province (No. 242102320072), the Youth Talent Support Project in Henan Province (No. 2024HYTP036) and the Innovation and Entrepreneurship Training Program for College Students of Henan Province (No. 202510078022).

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