

Article

Study on Multi-Factor Coupling Simulation and Improving Fire Evacuation Strategies in Old Multi-Story Residential Buildings

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Abstract

As urbanization accelerates in China, existing multi-story residential buildings constructed between 1980 and 2000 face increasing fire risks due to high occupant density and outdated fire safety codes. This study develops a multi-factor coupling simulation framework integrating BIM, PyroSim (2020), and Pathfinder (2020) to evaluate fire evacuation safety. Results suggest that kitchens located farther from stairwell entrances tend to impose greater smoke temperature and visibility hazards. Alternating evacuations may outperform uniform platform-based strategies. Concentrating slow-moving occupants on lower floors may improve evacuation efficiency, while counterflow and returning behaviors tend to cause the greatest obstruction on middle floors (5th–7th stories). Multi-factor coupling analysis indicates nonlinear thresholds: maximum safe occupancy decreases from 6.0 to below 4.0 persons per household as building height increases from seven to nine stories; exit widths beyond 0.95 m yield diminishing returns; and critical stairwell obstacle sizes decrease from 0.6 m to 0.3 m as household density increases. Three retrofit strategies were examined: adding outdoor stairs achieved a safety margin of 71.2 s; adding evacuation platforms raised safe occupancy from 3.5 to 4.5 persons per household; and installing kitchen sprinklers reduced the smoke concentration in stairwells. These findings may provide a useful reference for fire safety retrofitting in existing multi-story residential buildings.

Keywords: multi-story residential buildings; fire evacuation; PyroSim; Pathfinder; multi-factor coupling simulation



Academic Editor: Xavier Romão

Received: 19 May 2026

Revised: 25 June 2026

Accepted: 6 July 2026

Published: 13 July 2026

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1. Introduction

Against the backdrop of global urbanization and increasing climate risks [1], cities worldwide face growing challenges posed by multi-hazard emergencies and aging infrastructure [2]. In the context of China's 14th Five-Year strategy for building resilient cities and ongoing community pilot projects, urban areas are under heightened pressure to enhance their disaster resistance and prevention capabilities. Many existing multi-story residential buildings constructed between 1980 and 2000 are particularly vulnerable due to aging structures, high occupant density, and outdated fire codes. The combination of high heat release, rapid fire development, and intense smoke spread makes these buildings prone to severe casualties and property loss. National fire statistics shown in Figure 1 indicate that the number of fire incidents has increased notably since 2021 [3], particularly in multi-story

residential buildings. Fire hazards such as electric bicycle charging, storage of items in stairwells, and group rentals contribute to evacuation difficulties and exit blockages, presenting a fire safety concern that warrants urgent attention [4].

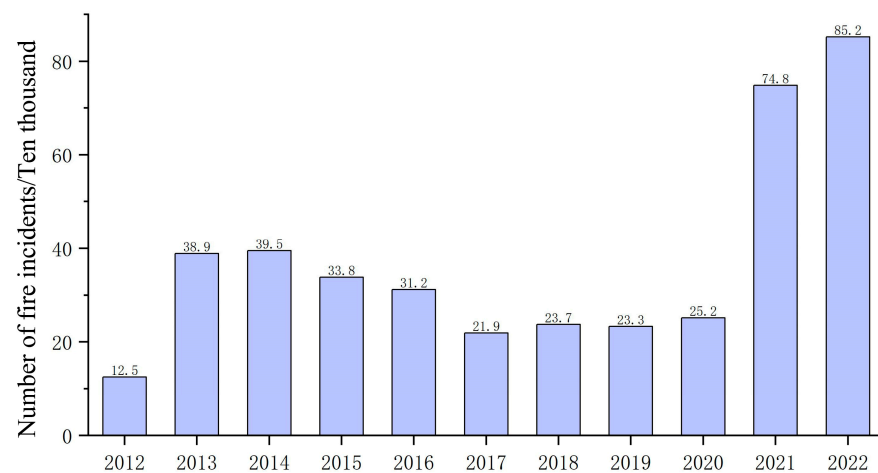


Figure 1. Statistics of fire incidents from 2012 to 2022.

Among various fire safety measures, evacuation is the core process for reducing casualties, and its efficiency directly affects life safety [5]. Empirical studies [6] show that population aging, an increasing proportion of individuals with mobility impairments, and complex building structures [7] may prolong evacuation times. Evacuation guidelines [8], emergency lighting, and environmental accessibility [9] may also significantly affect evacuation efficiency [10,11]. Runefors et al. [12] found that the evacuation of elderly occupants relied heavily on their surroundings, and assistance from neighbors may expedite the process. Wang [13] studied evacuation behavior in corridor-type high-rise building fires, while Zhang [14] developed an agent-based evacuation model for multi-story buildings, in which agents make decisions through interactions with their environment. However, the evacuation process in aging multi-story residential buildings is often subject to uncertainty and dynamic changes due to structural complexity and high occupant density, which may complicate management efforts. Castelblanco et al. [15] noted differences in the understanding of evacuation strategies between safety managers and residents. Sun et al. [16] proposed a hierarchical evacuation strategy using a gated recurrent unit integrated multi-agent proximal policy optimization (GRU-MAPPO) algorithm, with agents categorized into leaders and followers to improve evacuation efficiency.

To investigate evacuation risks in existing residential buildings, studies have increasingly employed coupled simulations combining Computational Fluid Dynamics (CFD)-based fire models [17] and agent-based evacuation models [18]. These studies typically evaluate performance using the Available Safe Egress Time (ASET) and Required Safe Egress Time (RSET) frameworks [19]. Zhang et al. [20] found through simulations that sprinkler systems were more effective than smoke barriers. Lu et al. [21] employed generative adversarial networks to predict evacuation scenarios in complex buildings. In terms of building design, incorporating external evacuation platforms, sky bridges, or refuge floors may help disperse crowds and improve safety margins [22,23]. Omidbeyk et al. [24] integrated Geographic Information Systems (GIS), Building Information Modeling (BIM), and reinforcement learning, finding that sky bridges may improve survival rates. Fang et al. [25] applied deep learning techniques to identify unsafe areas during fires, while Wang [26] found through virtual reality (VR) experiments that the height of wall signs was positively correlated with evacuation efficiency. These findings offer useful reference for evacuation design in residential buildings typical of the Lingnan region.

Recent studies have increasingly extended fire evacuation research from occupant movement analysis to broader emergency response operations. Shi et al. [27] and Lin et al. [28] demonstrated that navigation performance in complex and low-visibility environments is strongly influenced by spatial cognition, environmental familiarity, and psychological factors, highlighting the challenges faced by firefighters during search-and-rescue operations. To improve situational awareness and navigation efficiency, researchers have explored BIM-based indoor navigation systems, real-time information sharing platforms, and AR/VR-assisted training technologies [29–31]. The complexity of emergency response in residential buildings has also received growing attention. Studies have shown that stairwell congestion, vertical evacuation bottlenecks, dynamic fire conditions, and irregular building layouts may significantly affect both occupant evacuation and firefighter rescue activities [32]. Human behavioral uncertainties, including panic, delayed responses, counterflow movements, and heterogeneous responses to evacuation guidance, have also been identified as factors influencing evacuation outcomes and rescue effectiveness [33–35]. Recent advances in intelligent route planning, digital twins, environmental sensing, and firefighter monitoring technologies have further enhanced emergency response capabilities under challenging fire conditions [36–38]. Nevertheless, existing studies have largely examined navigation technologies, human behavior, and emergency response systems separately. Limited attention has been paid to their coupled interactions in aging multi-story residential buildings, where high occupant density, mobility-constrained residents, and complex spatial configurations may simultaneously affect evacuation performance and firefighter search-and-rescue operations.

Simulation technology can replicate fire scenarios in virtual environments, modeling the dynamics of fire spread, smoke diffusion, and occupant behavior. An emerging trend toward interdisciplinarity and intelligent simulation has been observed, with the coupling of BIM, PyroSim, and Pathfinder becoming increasingly common [39]. The introduction of digital twin technology may further improve the accuracy and efficiency of simulations, providing support for fire safety retrofit in existing multi-story residential buildings. Spearpoint et al. [40] compared Pathfinder and Evacuationz in simulating evacuation in high-rise structures. Li [41] combined PyroSim and Pathfinder simulations, suggesting that cross staircases may be more effective than straight staircases, which in turn may be preferable to parallel double staircases for evacuation management. While research has made considerable progress in fire modeling, evacuation simulation, and intelligent tools, studies on existing multi-story residential buildings remain limited. Localized parameter calibration and scenario validation have received insufficient attention. Empirical studies and localized simulations may therefore be needed to support performance-based fire safety design and optimize evacuation strategies in existing residential areas.

This study uses Shenzhen as a case study, focusing on a typical multi-story residential district. By integrating PyroSim, Pathfinder, and BIM, evacuation safety simulations were conducted to examine the influence of fire characteristics, building environments, and occupant attributes on the evacuation process. By comparing ASET and RSET, the mechanisms by which building design, occupant characteristics, and multi-factor coupling affect evacuation efficiency were evaluated. Based on the simulation results, a series of fire safety evacuation control strategies are proposed to improve evacuation efficiency and enhance the fire safety performance of existing multi-story residential buildings. The findings may offer practical reference for evacuation planning in similar residential settings and provide useful guidance for fire safety management.

2. Research Methods

2.1. Overview of Research Framework

A coupled simulation framework based on a Revit model was established, as illustrated in Figure 2. The Revit model of the residential building is exported in Industry Foundation Classes (IFC) format and imported into PyroSim for fire simulation and Pathfinder for evacuation simulation. PyroSim is used to simulate fire development and analyze smoke temperature, CO concentration, and visibility, from which the available safe egress time (ASET) is determined. Pathfinder is used to simulate occupant evacuation under different scenarios and calculate the required safe egress time (RSET). The quantitative comparison between ASET and RSET across different scenarios forms the basis for evaluating fire evacuation safety and informing retrofit recommendations for existing multi-story residential buildings.

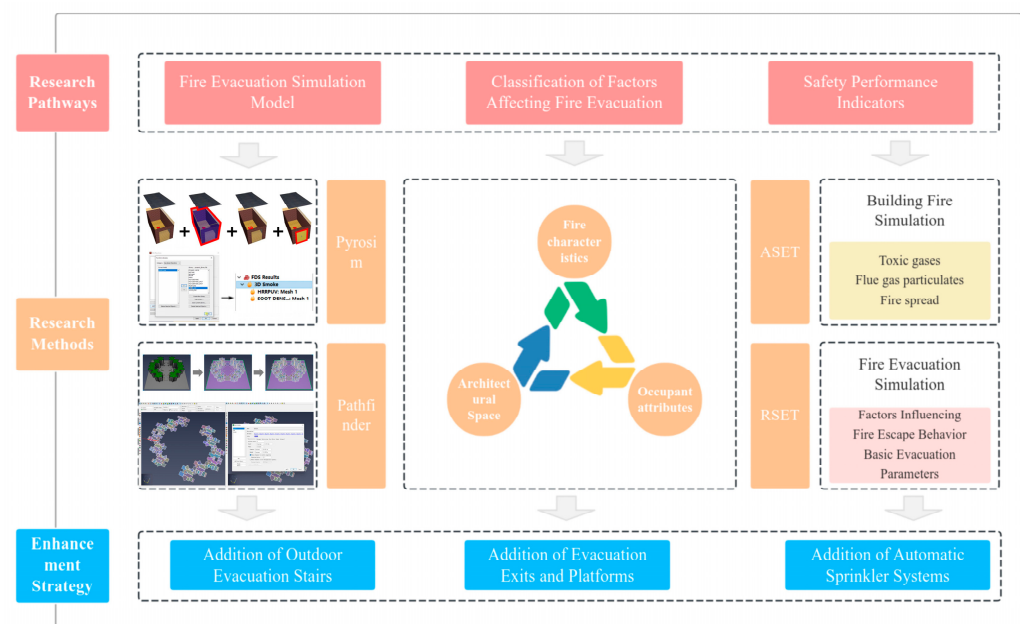


Figure 2. Research framework.

2.2. Classification of Factors Influencing Fire Evacuation Process

The complexity of fire evacuation in existing multi-story residential buildings stems from the dynamic coupling of three categories of factors: fire characteristics [42], building layout [43], and occupant attributes [44]. Their relationships are illustrated in Figure 3. Fire evolution serves as the primary driving force, while building layout regulates smoke spread and evacuation routes. Occupant behavior influences fire development and is affected by physiological and psychological conditions. The interactions among these three factors are notable: spatial configurations affect smoke diffusion and evacuation decisions, while occupant behavior may alter fire dynamics and the effectiveness of safety facilities. This multi-factor coupling introduces systemic risks and highlights the value of integrated modeling and simulation research.

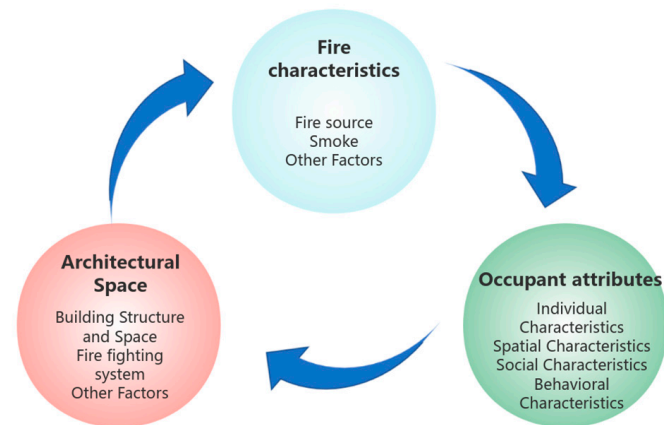


Figure 3. Dynamic coupling among fire characteristics, building space, and occupant attributes.

2.3. PyroSim and Pathfinder

In this study, PyroSim (2020) [45] is used to model the residential building geometry imported via IFC format, generate the computational grid, configure fire source parameters, and simulate smoke spread in the stairwell. Key outputs include time histories of temperature, CO concentration, and visibility at the stairwell entrance landing, which are used to determine ASET. Pathfinder (2020) [46] is used to model the six-building residential complex, configure occupant parameters including population distribution, walking speeds, and male-to-female ratio based on local census data, and simulate evacuation using the Steering mode to account for collision avoidance and pedestrian interactions. The evacuation time obtained from the simulation is used in the RSET calculation.

2.4. Safety Performance Indicators

2.4.1. Evaluation of Fire Safety Evacuation Time

The evacuation capacity of a building during a fire can be assessed by comparing the ASET (t_{ASET}) and the RSET (t_{RSET}) [47]. ASET (t_{ASET}) refers to the time from the onset of the fire to the moment when critical hazardous conditions reach threshold levels. This information can be obtained through a PyroSim simulation. In contrast, RSET (t_{RSET}) refers to the total duration from the initiation of evacuation to its completion after the occurrence of fire, reflecting the demand for evacuation. Following expression can be used to determine RSET:

$$t_{RSET} = t_{det} + t_{res} + t_{move} \quad (1)$$

where t_{det} is the time from fire ignition to detection and alarm, t_{res} is the response time of occupants to the fire alarm, and t_{move} is the time it takes for occupants to evacuate. Considering uncertainties such as panic and crowding during the evacuation process, an evacuation safety coefficient α is introduced into t_{move} , leading to the following expression:

$$t_{RSET} = t_{det} + t_{res} + (\alpha \cdot t_{move}) \quad (2)$$

where t_{s_move} is the evacuation time derived from simulation. Previous studies have adopted an evacuation safety coefficient ranging from 1.0 to 1.2 to account for uncertainties associated with occupant behavior, panic, and crowd congestion during evacuation [48]. In the present study, however, occupant movement was simulated using Pathfinder, which explicitly considers pedestrian interactions, queuing effects, and exit bottlenecks. The major evacuation uncertainties are therefore already incorporated into the simulation process. To avoid double-counting evacuation delays, α was set to 1.0 in this study. It should be noted that increasing α would proportionally increase the calculated t_{RSET} values. Since α acts as a uniform scaling factor on movement time, however, it would not alter the relative

comparisons among the different residential configurations examined in this study. The evacuation safety margin, denoted as t_{SURP} , is defined as the difference between ASET and RSET:

$$t_{SURP} = t_{ASET} - t_{RSET} \quad (3)$$

As illustrated in Figure 4, a larger t_{SURP} in fire evacuation time indicates longer preparation time for evacuation, signifying higher fire evacuation safety performance. For this study, the threshold value for the safety margin is established at 60 s.

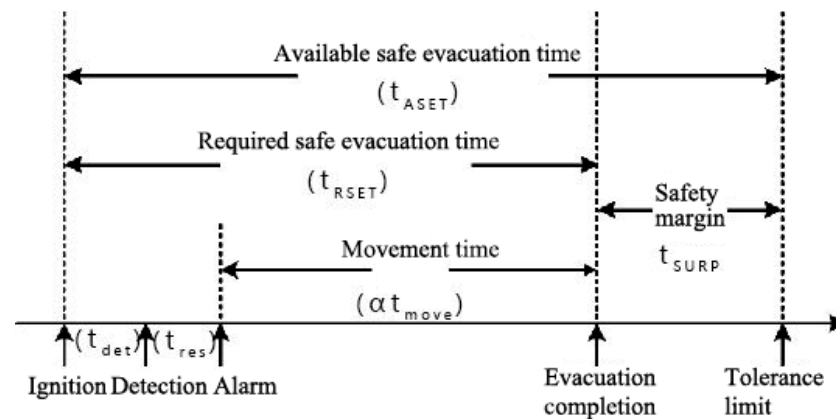


Figure 4. Safety evaluation of fire evacuation time.

2.4.2. Determination of Safety Factors in Fire Evacuation Simulation

In this study, a smoke temperature of 60 °C is adopted as the critical threshold [49]. High-temperature smoke accumulates near the upper parts of rooms, and inhalation of toxic gases such as CO significantly affects the evacuation process. Exposure to 1000 ppm of CO for 1 h can lead to loss of consciousness, while exposure to 1600 ppm for 20 min can result in dizziness or even coma. Therefore, a CO concentration of 1400 ppm is selected as the critical threshold. During a fire, the smoke height may fluctuate due to heat exchange and human disturbance. It cannot be determined solely based on visual line height and requires correction. The formula for calculating critical hazardous smoke height is

$$H_s > H_c = H_{PE} + 0.1 H_B \quad (4)$$

where H_s is the smoke layer height (m), H_c is the critical hazardous smoke height, H_{PE} is the average height of human eyes, and H_B is the story height.

According to the Report on Nutrition and Chronic Disease Status of Chinese Residents (2020) [50], the average heights of Chinese men and women aged 18–44 are 169.7 cm and 158.0 cm, respectively. Based on the principle of worst-case fire conditions, the average male height is set at 1.70 m, giving an HPE of 1.60 m. Using Equation (4), the critical hazardous smoke layer height is calculated to be 1.90 m.

Based on FDS calculations, the main factors influencing building fire evacuation include smoke temperature (°C), CO concentration (ppm), and visibility at smoke height (m) [51]. In accordance with the disaster scenario modeling guidelines of the National Institute of Standards and Technology (NIST), 60 °C is adopted as the threshold for thermal injury risk, a value supported by the thermal radiation flux-skin tissue damage correlation model. Regarding gaseous toxic hazards, carbon monoxide (CO) in combustion products is a primary cause of fire-related fatalities due to its high affinity for hemoglobin. Toxicological studies have shown [52] that CO exposure dose and consciousness impairment exhibit a time-varying relationship: when the environmental concentration reaches 1000 ppm, continuous inhalation for 60 min may cause central nervous system depression; when

the concentration rises to 1600 ppm, the neurotoxic effect accelerates and may lead to disorientation within 20 min. Based on this analysis, a CO concentration of 1400 ppm is adopted as the threshold for toxic gas injury risk. A visibility threshold of 5 m for evacuation in small enclosed spaces is commonly adopted in fire safety engineering studies [53,54]. The critical thresholds for these fire hazards are summarized in Table 1.

Table 1. Critical thresholds of fire hazards at height of 1.9 m.

Smoke Temperature at 1.9 m (°C)	CO Concentration at 1.9 m (ppm)	Visibility at 1.9 m (m)
60	1400	5

Note: 1 ppm = 10^{-6} .

3. Case Study and Analysis

3.1. Selection of Research Object

To ensure representativeness and generalizability, a comprehensive multi-dimensional screening system was established, taking into account factors such as floor area ratio, floor plan layout, building combinations, number of stories, construction period, and location. A typical case was required to feature local characteristics, including a configuration of 6–9 stories, unit-based floor plans, two-story evacuation platforms, and open ground floors, as well as high occupant density, complex spatial configurations, and a relatively high proportion of elderly residents and children. A residential cluster in Yuanling New Village, Shenzhen, was ultimately selected as the case study. The floor plans and on-site photographs of the selected site are shown in Figures 5 and 6, respectively. This case reflects the fire safety vulnerabilities commonly found in existing multi-story residential buildings. As noted in the preceding analysis, the ground level on the north side of the building is one floor higher than that on the south side. A platform therefore connects the first floor on the north side to the second floor on the south side, ensuring consistent building height and enabling the use of the second-floor platform on the south side for evacuation. Given the greater number of floors in the south-facing units and the complexity of the second-floor platform, this simulation focuses on south-facing residents (9 story).

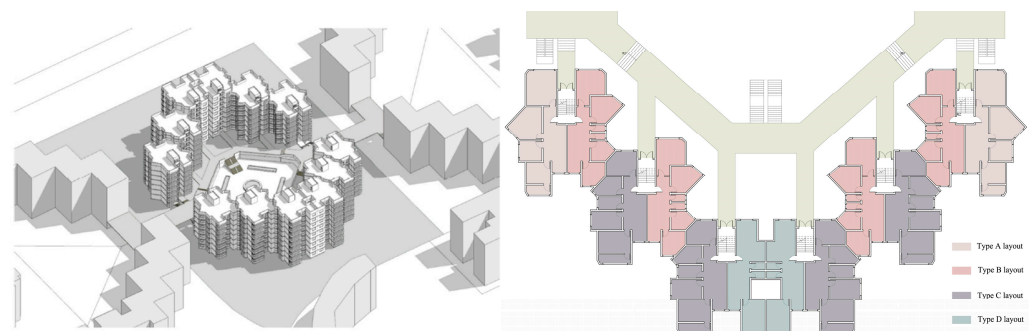


Figure 5. Floor plan of the southern part of a residential cluster in Yuanling New Village.



Figure 6. On-site images of Yuanling New Village.

3.2. Construction of BIM Model for Residential Area

Key parameters, including exterior wall dimensions, story heights, and landing dimensions, were obtained through field measurements. Room layout and dimensions of internal apartment units were derived from measurement data sourced from the Lianjia platform. Based on this information, a parametric family model was created in Revit. Building components, including floors, walls, doors, and windows, were categorized and checked for geometric conflicts. An IFC format model was then generated and exported. Critical parameters, including entrance door width, obstacle dimensions, and landing width, were subsequently adjusted based on the original Revit parametric model. Multiple evacuation comparison models were constructed, and the IFC export process was repeated for each configuration. This provided a reliable foundation for the subsequent fire evacuation simulations.

3.3. Fire Simulation Parameter Setting

3.3.1. Fire Source Parameter Setting

Fire combustion process simulations are broadly categorized into steady-state and unsteady-state models [55]. Steady-state models converge more readily due to their time-invariant parameter properties, while unsteady-state models rely on more complex aerodynamic calculations. This study employs an unsteady-state fire model in which the heat release rate from the fire source is proportional to the square of time, as expressed in the following equation:

$$Q = at^2 \quad (5)$$

where Q represents the heat release rate of the fire source (kW), a represents the fire growth coefficient (kW/s²), and t represents the fire development time (s).

A thorough analysis of kitchen fire data from the fire thermal database of the National Fire Research Laboratory of the United States was conducted [1]. A kitchen fire model with a peak heat release rate of 1879 kW was selected, with a cumulative energy release of 1452 MJ and a combustion duration of 15.75 min. The peak heat release rate was reached in 1.6 min. Based on the data file, an average heat release rate of 1700 kW during the fire growth stage was adopted as the simulated heat release rate. The US GSA 1985 standard specifies that the maximum evacuation time for civil buildings of fire resistance grades I and II is 6 min [54]. This duration was therefore adopted as the total fire simulation duration. By substituting the selected heat release rate and fire duration into Equation (5), the fire growth coefficient α was calculated to be 0.013 kW/s². Based on comparison with the fire growth coefficient table, this value corresponds to a medium-speed fire [1].

Based on kitchen fire data from the U.S. National Fire Research Laboratory [56], the average heat release rate during the growth phase is set at 1700 kW [57]. According to the General Services Administration (GSA) 1985 standard, the fire duration is established at 6 min, which corresponds to the maximum evacuation time for civil buildings. By substituting the values into Equation (5), the fire growth coefficient a is calculated to be 0.013 kW/s², classifying the fire as a slow growth fire. Following the principle of the worst-case scenario, two middle buildings from the nine-story southern block were selected for FDS simulation. The ignition point was set at the corner near the window of an open kitchen located on the west side of the second-floor connecting landing. In the simulation, the windows remained closed, while all doors on this floor were kept open.

3.3.2. Calculation of Simulation Grid Size

As Pyrosim (2020) software imposes high computational demands for FDS simulations, simulating all south-facing units with a full grid would substantially increase computational workload and simulation time. In addition, residents outside the affected unit are generally

at considerably lower risk than those within it. Based on the principle of minimizing fire hazard, the two tallest units (9 floors) in the middle of the south-facing building were selected for fire simulation in Pyrosim, as shown in Figure 7.

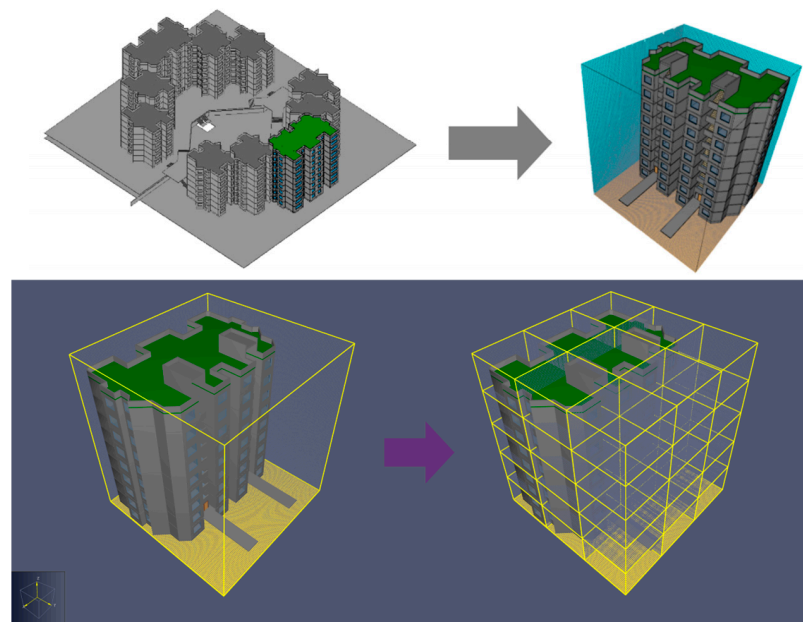


Figure 7. Selection of fire simulation model.

The FDS User Guide recommends assessing mesh resolution using the ratio of the characteristic fire diameter (D^*) to the grid size (δx). The parameter $D^*/\delta x$ represents the number of computational cells spanning the characteristic fire diameter, with larger values corresponding to finer mesh resolution. Previous FDS studies commonly classify $D^*/\delta x$ values of approximately 4, 10, and 16 as coarse, moderate, and fine mesh resolutions, respectively. When the heat release rate was 1700 kW, D^* was calculated to be 1.2 m using the D^* calculator. A grid size of 0.2 m was adopted, resulting in a $D^*/\delta x$ ratio of approximately 6.0. Given the large computational domain and the need to evaluate multiple residential scenarios, the selected mesh size was considered a practical compromise between computational efficiency and simulation resolution. The resulting computational domain contained 1,779,570 computational cells, as shown in Figure 8.

Calculate D^*

Input	
Q_{dot}	= 1700 kW
dens	= 1.204 kg/m ³
c_p	= 1.005 kJ/(kg • K)
T	= 293 K
g	= 9.81 m/s ²

Output	
D^*	= 1.185719 m
Mesh $D^*/5$	= 0.237144 m
Mesh $D^*/10$	= 0.118572 m
Mesh $D^*/20$	= 0.059286 m

This software is provided as is, and no claim is made as to the accuracy or suitability of this software. The user takes full and exclusive responsibility for using this software.

Fire Plumes

Plume Temperatures

For fire plumes, a measure of how well the flow field is resolved is given by the non-dimensional expression $D^*/\delta x$, where D^* is a characteristic fire diameter

$$D^* = \left(\frac{\dot{Q}}{\rho_{\infty} c_p T_{\infty} \sqrt{g}} \right)^{\frac{2}{3}}$$

and δx is the nominal size of a mesh cell¹¹. The quantity $D^*/\delta x$ can be thought of as the number of computational cells spanning the characteristic (not necessarily the physical) diameter of the fire. The more cells spanning the fire, the better the resolution of the calculation. It is better to assess the quality of the mesh in terms of this non-dimensional parameter, rather than an absolute mesh cell size. For example, a cell size of 10 cm may be “adequate,” in some sense, for evaluating the spread of smoke and heat through a building from a sizable fire, but may not be appropriate to study a very small, smoldering source.

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Figure 8. Mesh size calculation.

The initial environmental conditions for the simulation were set as follows: an indoor temperature of 25 °C, a relative humidity of 50%, an atmospheric pressure of 101,325 Pa, and an initial indoor airflow velocity of zero. Since all windows were assumed to be closed, external meteorological conditions were neglected, and the computational domain was defined as a fully enclosed indoor environment without external wind effects.

A formal grid convergence analysis was not conducted in this study, and some numerical uncertainty may remain in the absolute values of the predicted hazard development times. The same mesh resolution, fire source characteristics, modelling assumptions, and boundary conditions were applied consistently across all simulation scenarios. The simulation results are therefore considered appropriate for comparative evaluation of relative fire evacuation performance among different residential configurations. This limitation will be taken into account when interpreting the results.

3.3.3. Parameter Setting of Occupant Evacuation Simulation

According to the Pathfinder user manual, two simulation modes are available for personnel evacuation: SFPE and Steering. Given that emergency evacuation in fire scenarios is subject to numerous interfering factors, the Steering mode was adopted for the evacuation simulation. Based on a preliminary investigation of the case study building, the following parameters were established. The building complex consists of six blocks, with an average of 4.5 occupants per household. Each block has a stairwell serving two households, and each household contains three rooms, forming a one-staircase-two-household configuration. The two outermost blocks on the east and west sides are seven stories high, with the number of floors increasing progressively toward the middle until the two central blocks reach nine stories. A two-story platform connects the six blocks. The estimated number of residents per floor is 54, with an increment of 0.5 occupants per household, increasing to 6 residents per floor. Based on an assumed gender ratio of 1:1 [58], the average walking speed was set at 1.2 m/s for male occupants and 1.1 m/s for female occupants. The clear width of the exit door for each unit was set to 0.95 m, the width of the exterior platform to 4.4 m, and the width of the platform connecting to the entrance to 2.5 m.

4. Results and Discussion

4.1. Assessment of Current Evacuation Safety in Residential Area

As shown in Figure 9, the smoke temperature reaches the critical threshold of 60 °C at 134.3 s, but the isotherm does not fully cover the stairwell entrance landing. The CO concentration reaches the critical threshold of 1300 ppm at 172.6 s, with a smaller affected area compared to the temperature-affected zone. Visibility decreases to the critical threshold of 5 m at 185.9 s, fully covering the stairwell entrance landing. Among the three hazard factors, namely smoke temperature, CO concentration, and visibility, only visibility reaches its critical threshold within the simulation period, at 185.9 s. The available safe egress time (tASET) is therefore determined to be 185.9 s. The evacuation simulation shows that the last occupant exits the building at 124.7 s. The movement time is 124.7 s, and the detection time and response time are each taken as 5 s in accordance with reference [56]. The required safe egress time (tRSET) is therefore 134.7 s. The safety margin, calculated as the difference between tASET (185.9 s) and tRSET (134.7 s), is 51.2 s.

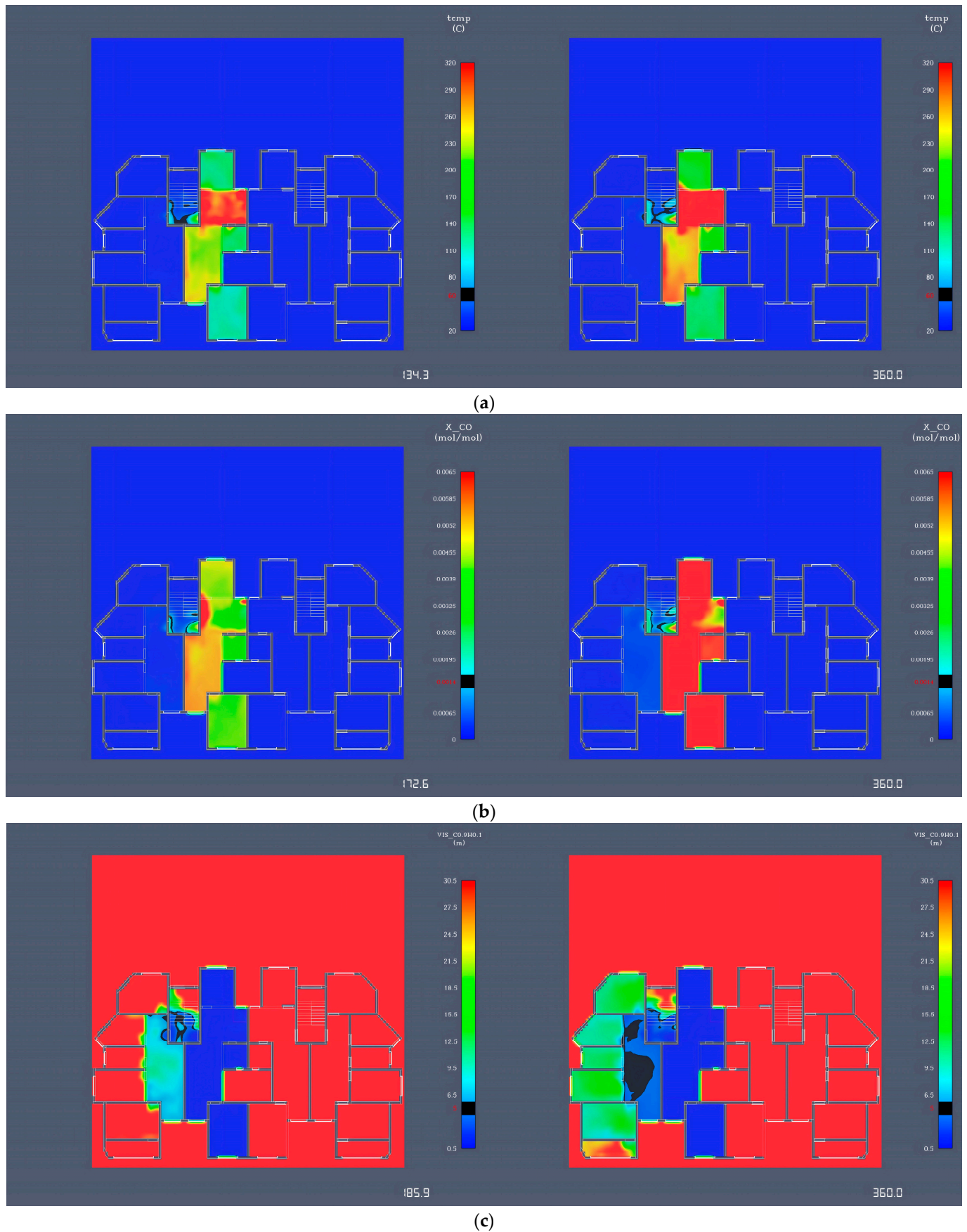


Figure 9. (a) Smoke temperature, (b) CO concentration, and (c) visibility.

In this study, the total available time before evacuation is divided into two parts. The first part is the fire detection and alarm time, consisting of the detection time (5 s) and the response time (5 s), giving a total of 10 s. The second part is the safety margin of 51.2 s, representing the time available for occupant preparation. In accordance with fire safety standards, a pre-evacuation preparation time of at least 60 s is required, giving a total required time of 70 s when combined with the 10 s alarm time. The combined total of the alarm time (10 s) and the safety margin (51.2 s) is 61.2 s, which falls below the required 70 s. These findings suggest that the available preparation time may be insufficient, and that potential safety concerns may exist in the fire evacuation process under the condition of an average of 4.5 residents per household.

4.2. Simulation Analysis of Building Spatial Factors

4.2.1. Location of Fire-Involved Kitchen

As shown in Figure 10, fire simulations were conducted in kitchens located in different positions across four residential apartment layouts (A, B, C, and D), while keeping the following variables constant: fire reaction type, CO release rate, fire source size, heat release rate, fire growth coefficient, building materials, computational grid, response time, and initial temperature. The three fire hazard factors evaluated were smoke temperature, CO concentration, and visibility.

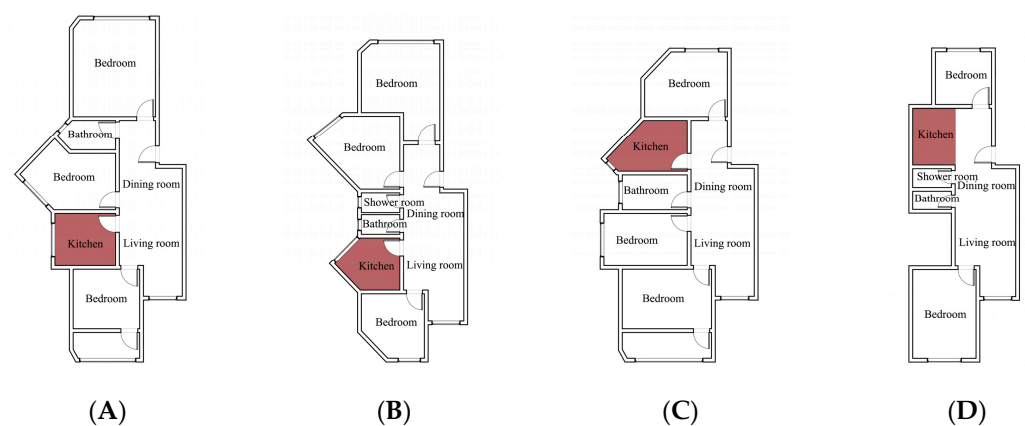


Figure 10. Four residential apartment layouts in Yuanling New Village: (A) layout A; (B) layout B; (C) layout C; and (D) layout D.

The simulation results are shown in Figure 11. For Layout A, the smoke temperature reaches its maximum impact on the stairwell at 204.6 s but does not pose a hazard to safe evacuation within the simulation period. The CO concentration reaches its maximum impact at 190.3 s and also does not endanger evacuation safety. Visibility begins to impair stairwell evacuation safety at 190.5 s. For Layout B, the smoke temperature reaches its maximum impact at 190.3 s without endangering evacuation. The CO concentration reaches its maximum impact at 229.7 s without endangering evacuation. Visibility reaches its maximum impact at 212.8 s and causes a minor effect on evacuation safety toward the end of the simulation. For Layout C, the smoke temperature reaches its maximum impact at 209.5 s and may endanger evacuation safety. The CO concentration reaches its maximum impact at 221.2 s without endangering evacuation. Visibility reaches its maximum impact at 201.2 s and may endanger evacuation safety. For Layout D, the smoke temperature reaches its maximum impact at 175.8 s without endangering evacuation. The CO concentration reaches its maximum impact at 172.6 s without endangering evacuation. Visibility reaches its maximum impact at 185.9 s and may endanger evacuation safety.

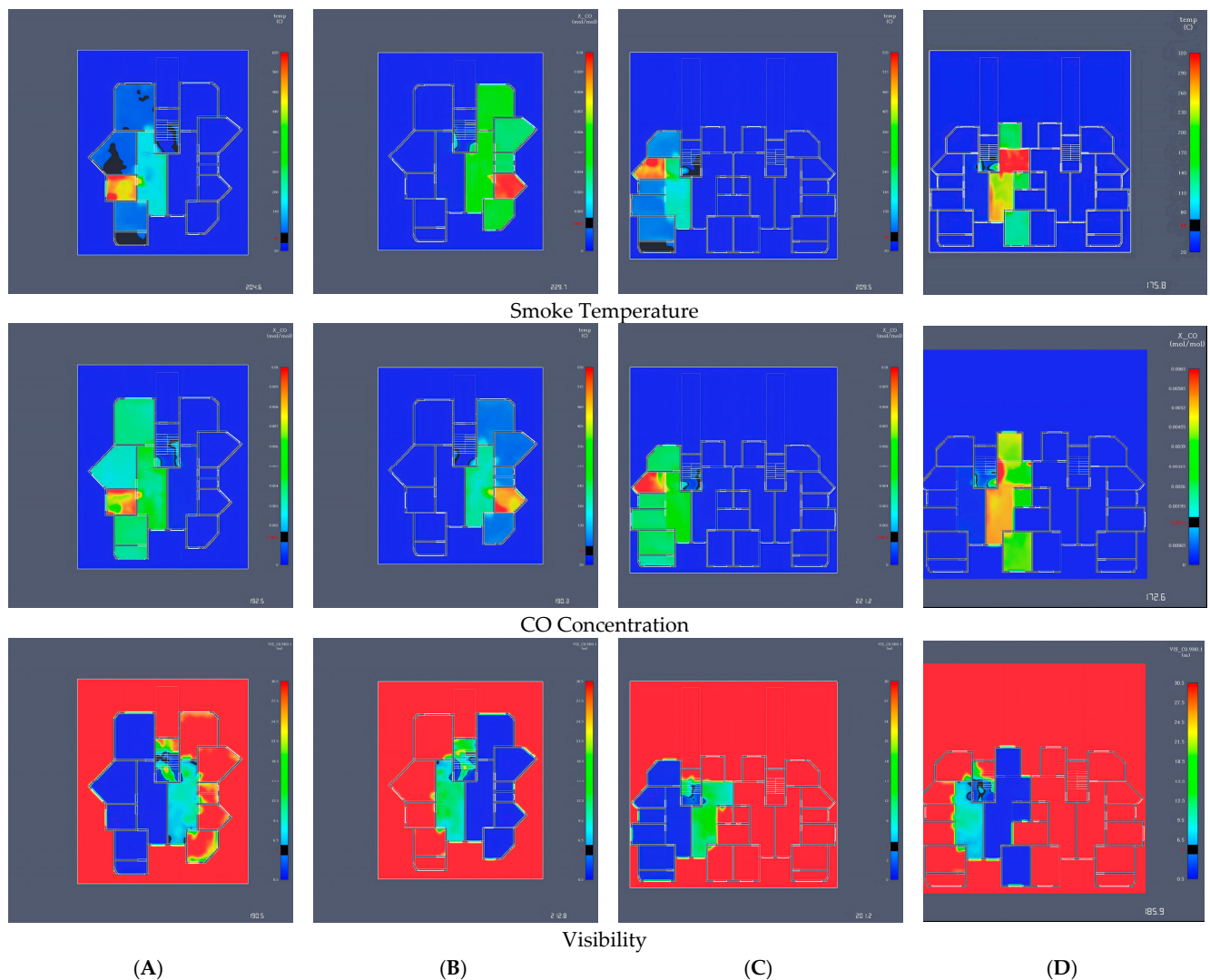


Figure 11. Stairwell slices of smoke temperature, CO concentration, and smoke visibility for four residential apartment layouts. Columns (A–D) represent the four residential apartment layouts, while the first, second, and third rows represent smoke temperature, CO concentration, and visibility, respectively.

The hazard rankings for stairwell smoke temperature are $D > C > A > B$; for CO concentration: $C > D > A > B$; and for visibility: $D > C > A > B$. These results suggest that in layouts where the kitchen is located farther from the entrance door (C and D), fire smoke takes longer to reach the stairwell, but the overall hazard severity of smoke temperature and visibility in these layouts tends to be greater than in layouts A and B. Between the two layouts with kitchens near the entrance door, the open kitchen design in Layout A allows smoke to spread more readily into the stairwell, resulting in greater effects on temperature and visibility, while the CO concentration in the stairwell is relatively lower as CO disperses earlier into the living room area.

4.2.2. Different Evacuation Routes

Evacuation routes were categorized into three types: (1) using only the first-floor exit; (2) using the first-floor exit for the first floor and platforms for the second floor and above, referred to as second-floor platform evacuation; and (3) using the first-floor exit for odd-numbered floors and platforms for even-numbered floors, referred to as alternating evacuation. Under the original conditions, relying solely on the first-floor exit resulted in

the longest evacuation time. The evacuation times for second-floor platform evacuation and alternating evacuation were found to be similar, as shown in Figure 12a. When the width of the second-floor exit was set at 0.6 m, alternating evacuation required less time than second-floor platform evacuation. This difference tended to become more pronounced as the number of occupants increased, as shown in Figure 12b. These findings suggest that when exits are obstructed, the alternating evacuation strategy may be more effective in improving evacuation efficiency compared to second-floor platform evacuation.

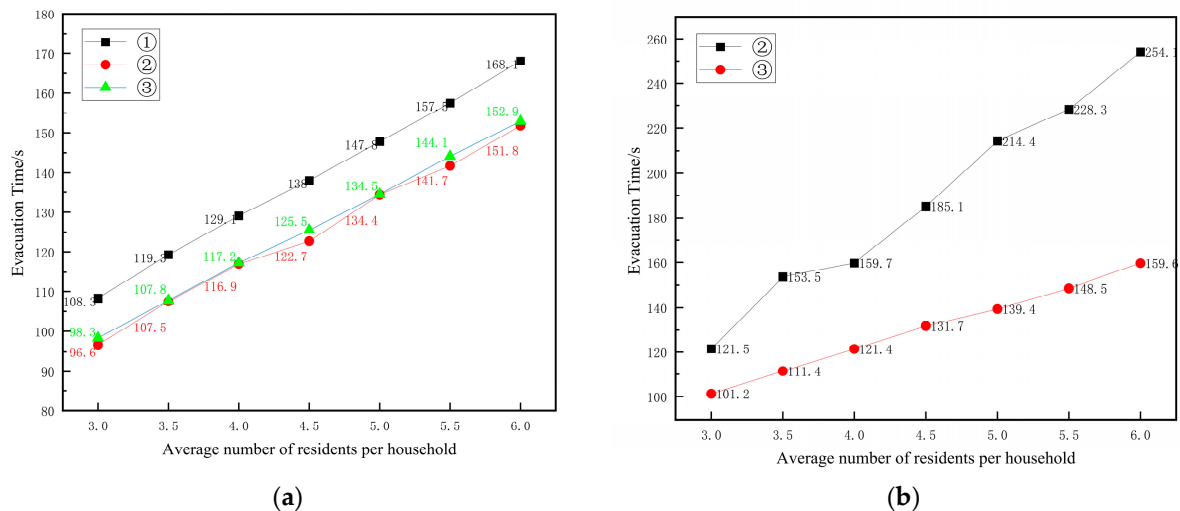


Figure 12. (a) Evacuation time for three types of evacuation routes. (b) Evacuation time for two types of evacuation routes when the width of the second-floor exit was set at 0.6 m.

4.3. Simulation Analysis of Occupant Attributes

The evacuation scenario and occupant parameters in this section follow the configuration established in Section 3.3. All occupants are initially located in their respective apartments. The male-to-female ratio is set at 1:1, with walking speeds of 1.2 m/s for male occupants and 1.1 m/s for female occupants. The evacuation route proceeds from each apartment through a 0.95 m wide door, down the staircase, and across the second-floor platform (widths of 4.4 m and 2.5 m) to the final safe exit. Although the ground floor and the second floor are not internally connected, all occupants on the ground floor are also required to evacuate. This is based on the precautionary principle: in the event of a fire, structural damage, or collapse cannot be ruled out, and any potential risk necessitates immediate evacuation of the entire building. Regarding age distribution, data from the Shenzhen Seventh National Population Census indicate that the proportion of elderly residents aged 65 years and above in the study area is 3.22%, which is considerably lower than the national average. Age has therefore not been introduced as an independent categorical variable. The potential effect of reduced mobility is addressed in Section 4.3.2 through the parametric definition of slow-moving occupants at walking speeds of 0.9 m/s, 0.6 m/s, and 0.3 m/s. The Steering mode in Pathfinder was adopted for the evacuation simulation to capture collision avoidance and realistic pedestrian interactions.

4.3.1. Different Numbers of Residents per Household

Evacuation times were simulated for an average of 3.0 to 6.0 persons per household, with an increment of 0.5 persons per household. The results are illustrated in Figure 13a, and the corresponding safety margins are shown in Figure 13b. The results indicate that RSET increases with the number of residents. When the average is 4.0 persons per household, the safety margin is 59.0 s, which is close to the critical value. When the average number of persons per household is 3.5 or fewer, the safety margin exceeds 60 s,

indicating that evacuation may be completed within the required time. When the average reaches 4.0 persons per household, the safety margin decreases to 59 s, falling below the 60 s threshold, suggesting insufficient evacuation capacity. When the average rises to 4.5 persons per household, the safety margin drops further to 53.2 s, which is below the critical threshold.

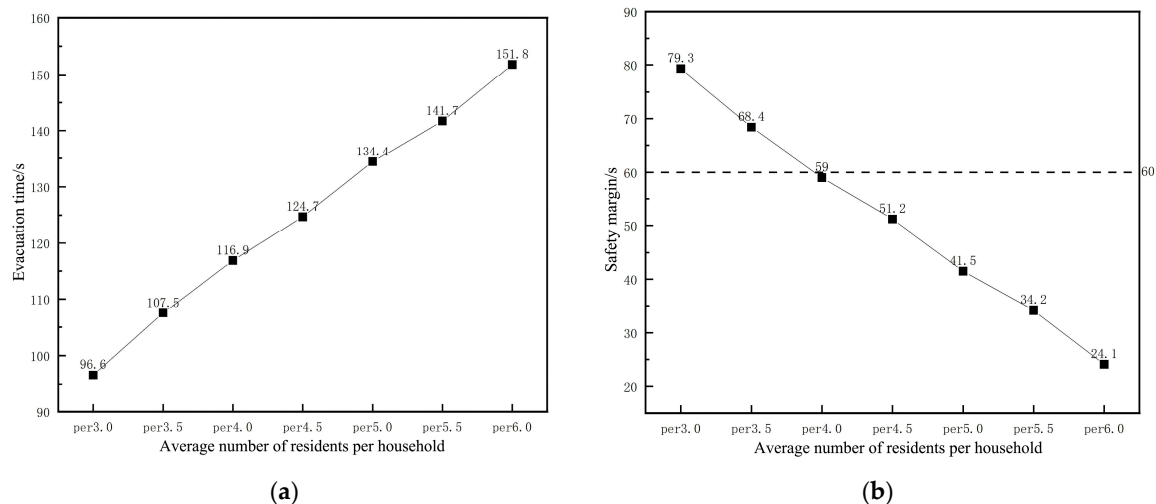


Figure 13. (a) Evacuation time and (b) safety margin for different household sizes. The dashed line indicates the 60 s safety margin threshold, which was used to assess compliance with the evacuation safety criterion; values above this threshold are considered acceptable.

4.3.2. Proportion of Slow-Moving Occupants

Elderly individuals, children, and other residents with restricted mobility may move at speeds lower than their normal walking speed during a fire. Slow-moving occupants were therefore categorized into three levels: slightly slow (0.9 m/s), slow (0.6 m/s), and very slow (0.3 m/s). A performance-based simulation method was adopted to examine the effect of different proportions and floor distributions of slow-moving occupants on overall evacuation time.

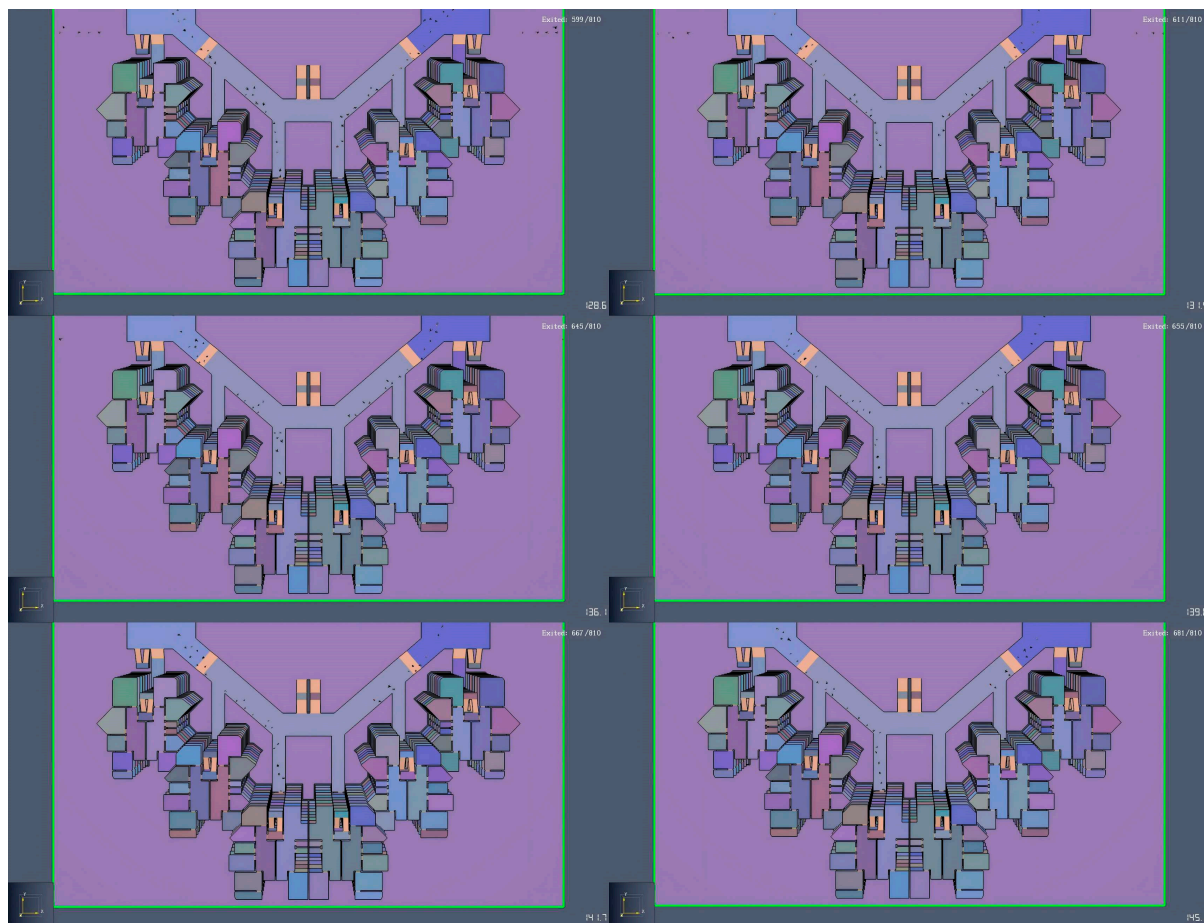
The proportion of slightly slow-moving occupants was varied by keeping the base household size constant at 4.5 persons and increasing the number of slow-moving occupants in increments of 0.5 persons per household, from 0 to 3.0 persons. The results, shown in Figure 14a,b, suggest that as the proportion of slightly slow-moving occupants increases, the total evacuation time becomes longer, indicating that differences in mobility may have a substantial effect on fire evacuation safety.

4.3.3. Counterflow and Returning Behaviors

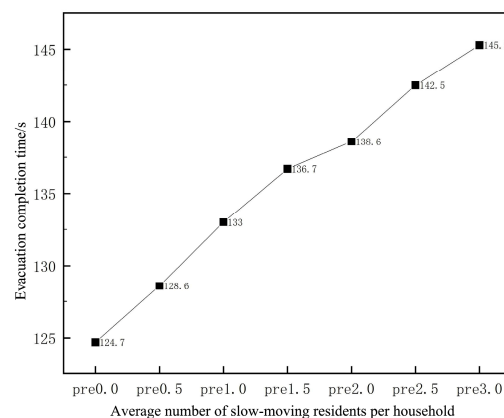
Two types of atypical evacuation behaviors were simulated to quantitatively examine their effects on fire evacuation: counterflow and returning.

Counterflow refers to evacuees moving in the opposite direction of the main evacuation flow [59]. The simulated variables include the total number of evacuees, the number of counterflow individuals, their movement timing and speed, the target floor, the dwell time upon reaching that floor, and the subsequent evacuation route. The average household size was set at 4.5 persons, and the counterflow individuals' walking speed was set equal to the normal walking speed. The evacuation process showed that the time from the start of evacuation to reaching the safe exit is approximately 9 s. For observation purposes, counterflow individuals wait at the safe exit for 10 s, then move to the target floor, where the dwell time is set at 20 s, after which they evacuate. The simulation records both the forward flow evacuation completion time and the counterflow evacuation completion

time. The results shown in Figure 15 suggest that a small number of counterflow evacuees (1–2 persons) has a limited effect on the main evacuation flow. Obstruction tends to be greatest when counterflow occurs on middle floors (5–7), with less effect on the ground or top floors. As the number of counterflow evacuees increases beyond two, the obstruction effect on forward flow becomes stronger, and counterflow to higher floors may pose a greater risk to both the counterflow individuals and overall evacuation efficiency. Regarding counterflow individuals themselves, when counterflow occurs on the 2nd or 3rd floor, their evacuation time is shorter than that of forward-flow individuals. When counterflow exceeds the 4th floor, their evacuation time becomes longer than that of the forward flow.



(a)



(b)

Figure 14. (a) Time slices and (b) completion times of evacuation with different proportions of slightly slow-moving residents.

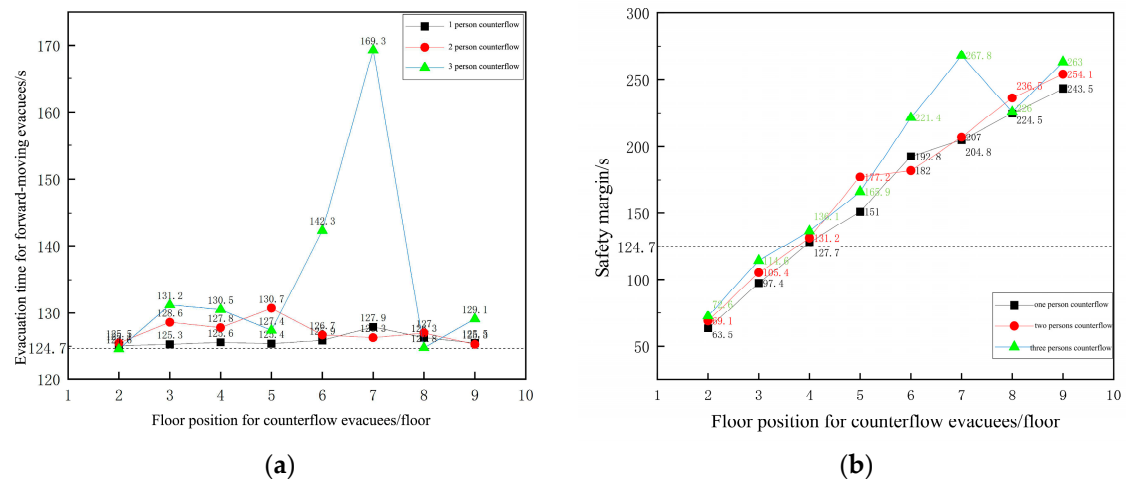


Figure 15. (a) Evacuation time and (b) safety margin for different floors and household sizes under counterflow scenarios.

Returning behavior refers to evacuees who, after reaching the safe exit, turn back to their original location and then evacuate again. The simulated variables include the number of residents, walking speed, number of returnees, return speed, initial floor, and dwell time at the safe exit before returning. The average household size was set to 4.5 persons, the returnees' speed was set to the normal walking speed, the decision-making dwell time at the safe exit was set to 10 s, and the activity time at the original location was set to 20 s. The returning evacuation completion time is defined as the time from the returnee's first arrival at the safe exit, through the decision-making pause, returning to the original location, completing activities there, and then re-evacuating to the safe exit. The results shown in Figure 16 suggest that returning from the ground floor or the top floor has a limited effect on overall evacuation. When the number of returnees is 1 or 2, the greatest obstruction tends to occur when returning from the 6th floor. When the number is 3, the greatest obstruction tends to occur when returning from the 4th floor. While the effect of returning on overall evacuation delay appears smaller than that of counterflow, it may substantially increase the evacuation time for the returnees themselves. When returning occurs on the 2nd floor, the returnee's evacuation time is shorter than the normal evacuation completion time. Returning from the ground floor poses a relatively low risk, while returning to higher floors may lead to a disproportionately higher personal risk.

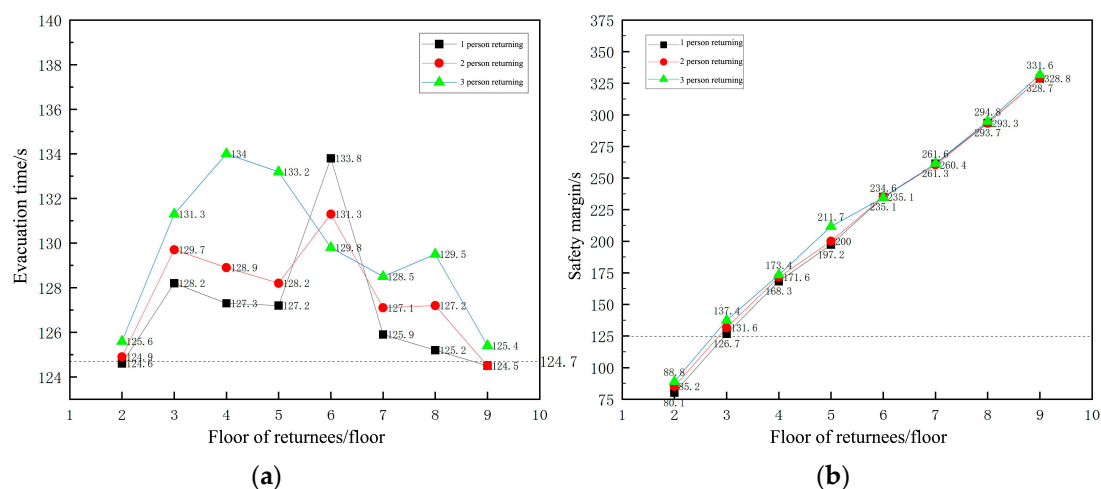


Figure 16. (a) Evacuation time and (b) safety margin for different floors and household sizes under returning scenarios.

4.4. Multi-Factor Coupling Evacuation Simulation Analysis

4.4.1. Building Stories and Occupant Density

Occupant density introduces uncertainty into the simulation results. Evacuation times were simulated for buildings of different numbers of stories with increasing average numbers of residents per household, and the corresponding safety margins were evaluated. The evacuation completion times and safety margins for 7-story, 8-story, and 9-story buildings are shown in Figures 17a and 17b, respectively. The results suggest that as the number of stories decreases, the tolerance for a higher average number of residents per household tends to increase while still allowing safe evacuation. Under the simulated conditions, the maximum safe average number of residents per household is approximately 6.0 for 7-story buildings, less than 5.0 for 8-story buildings, and less than 4.0 for 9-story buildings.

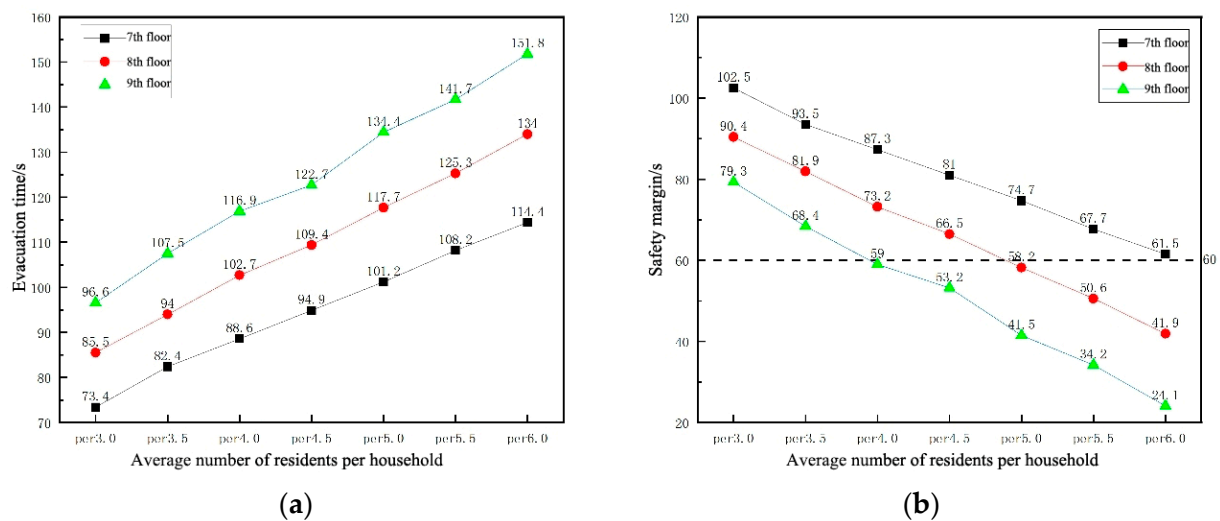


Figure 17. (a) Evacuation time and (b) safety margin for different stories.

4.4.2. Proportion of Slow-Moving Occupants and Floor Distribution

In this study, slow-moving occupants were redistributed from higher floors to lower floors while keeping the overall proportion constant. Evacuation times were simulated for scenarios in which slow-moving occupants did not occupy the top three floors, and the results are shown in Figure 18. The results suggest that concentrating slow-moving occupants on lower floors may improve overall evacuation efficiency compared to distributing them across higher floors. When the average number of slow-moving occupants per household is 0.5, the improvement is minimal. When it reaches 1.0, evacuation time decreases more notably. The variation in results is primarily associated with the proportion of slow-moving occupants, their walking speed, and their floor position. These findings suggest that under specific conditions of speed and density, concentrating slow-moving occupants on lower floors may improve evacuation efficiency, while their presence on higher floors may hinder normally moving occupants.

4.4.3. Occupancy of Outdoor Exit Evacuation Pathways and Household Density

Simulations were conducted to assess evacuation times and safety margins for outdoor exit widths ranging from 0.45 m to 1.05 m, with an increment of 0.05 m, across different average household sizes. The results are shown in Figure 19. As exit width increases, evacuation times decrease across different average household sizes. However, beyond a certain threshold, further increases in exit width yield diminishing reductions in evacuation time. This threshold is identified at an exit width of 0.95 m. As shown in Figure 19, when the average number of residents per household is 3.0, safety margins fall below the standard

value when the exit width is 0.65 m or less. When the average number of residents per household increases slightly to 3.5, safety margins fall below the standard value when the exit width is 0.80 m or less.

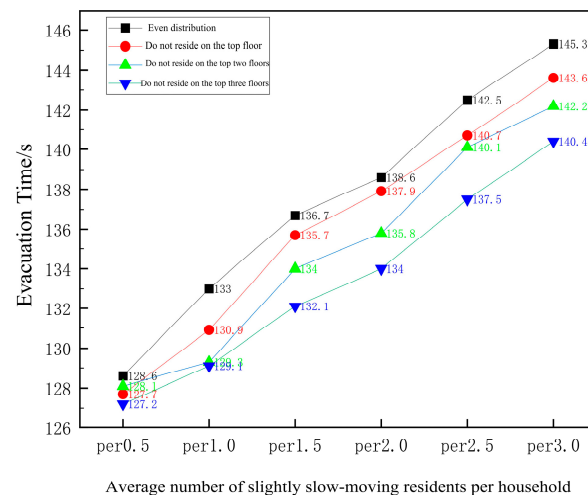


Figure 18. Evacuation completion time for different proportions of slightly slow-moving occupants.

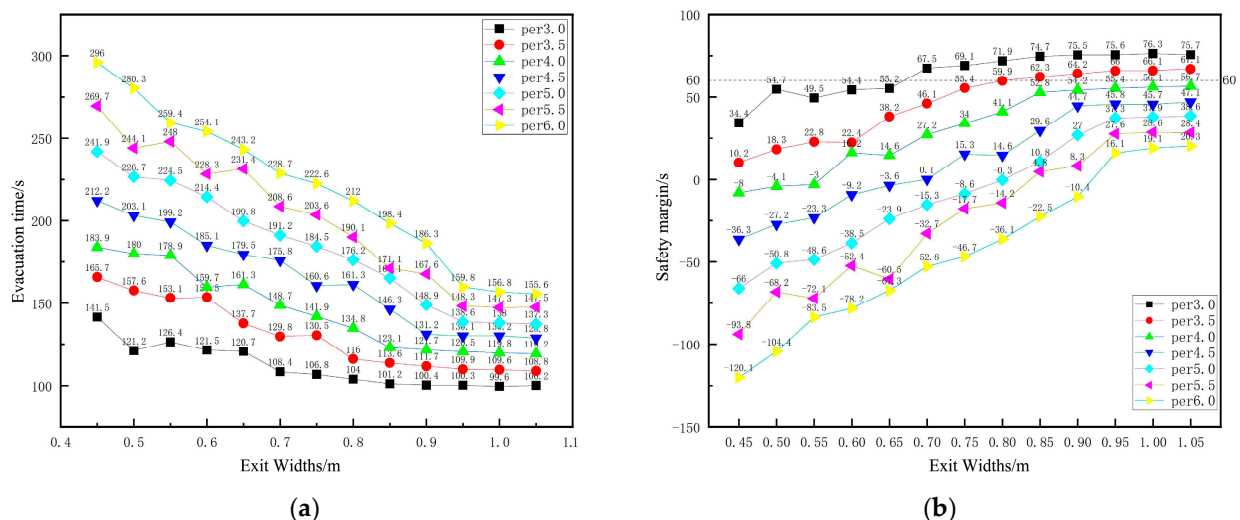


Figure 19. (a) Evacuation time and (b) safety margin with respect to exit widths.

4.4.4. Stairwell Obstacle Size and Household Density

Using increments of 0.1 m for both length and width, simulations were conducted to analyze evacuation times and safety margins based on varying household sizes while considering obstacle sizes on stair landings, ranging from 0.0 m × 0.0 m to 0.8 m × 0.8 m. The results are illustrated in Figure 20. The analysis shows that when the obstacle size surpasses a certain threshold, the evacuation time increases significantly. This threshold decreases as residential density increases. For average household sizes of 3.0, 4.0, 5.0, and 6.0, the corresponding critical obstacle sizes are approximately 0.6 m, 0.5 m, 0.4 m, and 0.3 m, respectively.

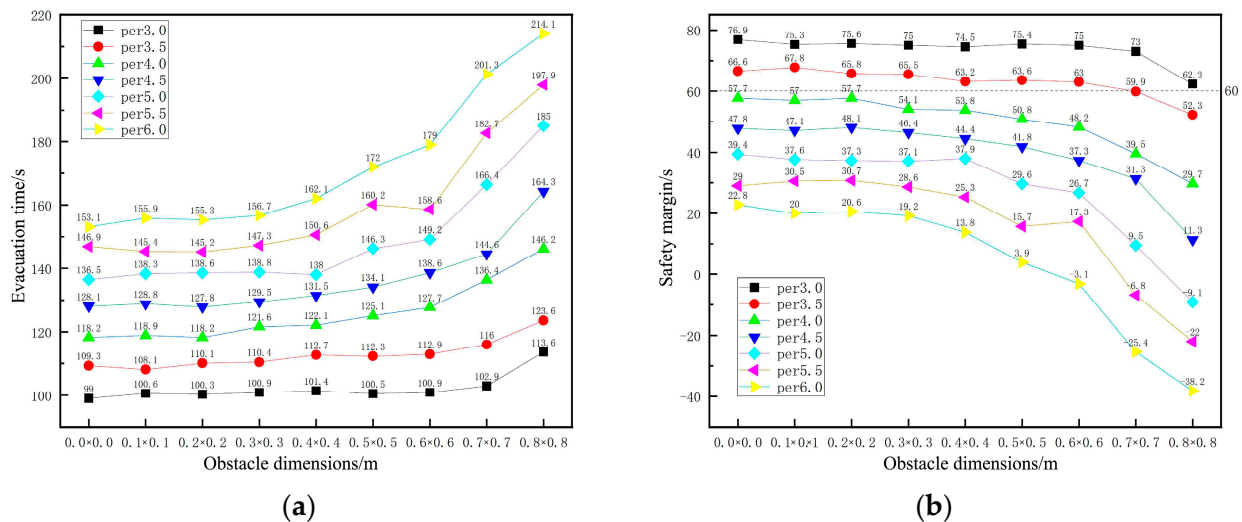


Figure 20. (a) Evacuation time and (b) safety margin for various obstacle sizes.

4.4.5. Platform Occupancy Width and Household Density

Simulations showed that the occupancy width of the stairwell-connected platform begins to affect evacuation time once it exceeds a certain level. Compared with obstacle dimensions, the threshold of platform occupancy width that affects evacuation time is more consistent across different household densities. When the average number of residents per household is 3.0, the threshold at which platform occupancy width begins to affect evacuation time is 1.4 m. When the average exceeds 3.0 persons per household, the threshold decreases to 1.2 m. With an average of 3.0 persons per household, the safety margin exceeds the standard value when the platform occupancy width reaches 1.6 m or greater. When the average number of residents per household increases to 3.5, the safety margin falls below the standard value for platform widths of 1.4 m or greater, as shown in Figure 21.

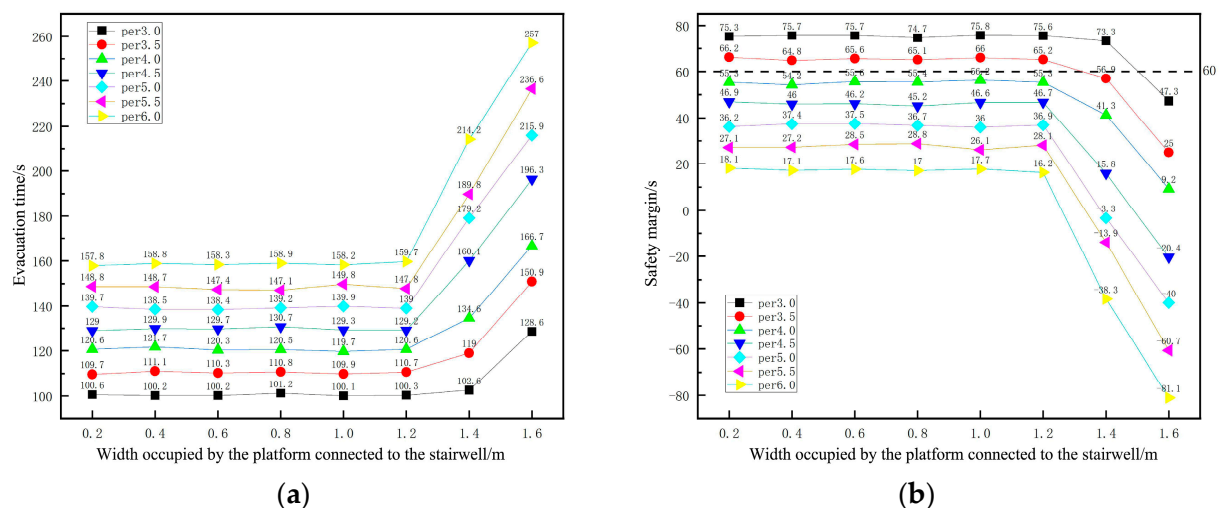


Figure 21. (a) Evacuation time and (b) safety margin for platform occupancy widths.

5. Safety Performance Enhancement Strategies

5.1. Addition of Outdoor Evacuation Stairs

The addition of outdoor evacuation stairs in existing multi-story residential buildings may substantially improve evacuation capacity. Building codes require the clear width of stairs to be at least 0.8 m, preferably constructed from steel or reinforced concrete, with spiral staircases avoided. Steps should be designed ergonomically, and stairs should be distributed evenly around the building to facilitate rapid evacuation. As shown in Figure 22, two retrofit schemes are proposed for Yuanling New Village: one involves adding a single flight of stairs connecting to the second-floor platform, while the other involves adding two flights of stairs connecting to the third-floor platform. The simulation results suggest that adding one floor of stairs achieves a safety margin of 71.2 s at an average of 4.5 residents per household, meeting the standard requirement. Although adding two flights of stairs yields a higher safety margin, the improvement is limited at low occupancy and tends to diminish at higher occupancy, while also increasing path complexity (Figure 23). The appropriate number of staircases should therefore be determined based on occupancy levels and floor layouts, with simulations used to balance safety margins and evacuation efficiency.

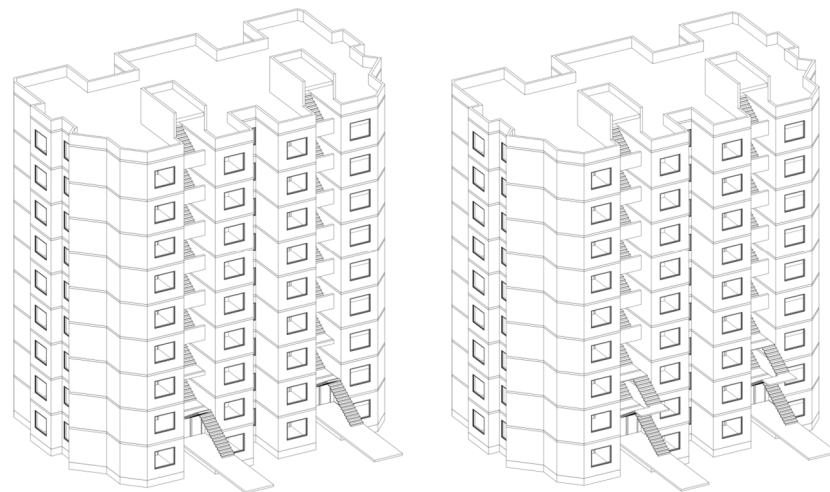


Figure 22. Addition of one floor of evacuation stairs and two floors of evacuation stairs.

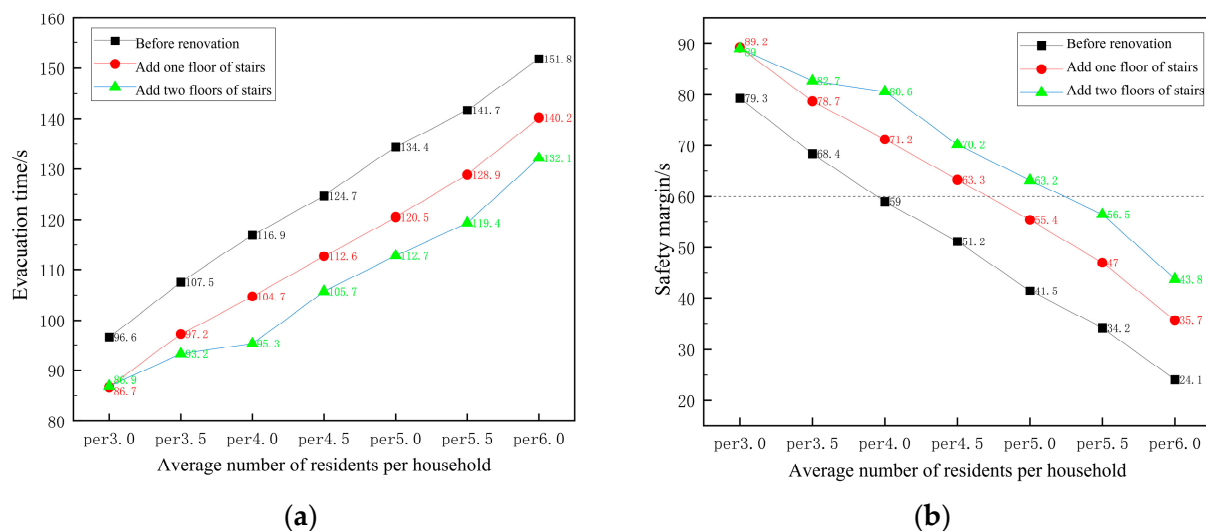


Figure 23. Comparison of (a) evacuation times and (b) safety margins before and after renovation for different household sizes.

5.2. Addition of Evacuation Exits and Platforms

In aging multi-story residential buildings, increased occupancy is associated with reduced evacuation performance. Incorporating additional escape passages and outdoor platforms may improve emergency evacuation efficiency. Possible retrofit strategies include the addition of safety doors near first-floor corridors or stairwells, expanding existing exits to reduce congestion, and creating platforms on the second floor and above to serve as refuge or transfer points. The results showed that an external platform width of 0.9 m and a stairwell-connected platform width of 1.3 m had no significant effect on evacuation time across the simulated occupancy levels. Based on these findings, an external platform width of 0.9 m and a stairwell-connected platform width of 1.3 m were adopted, and an additional outdoor evacuation platform was added on the third floor above the existing second-floor platform. The model configurations before and after retrofit are shown in Figure 24. Evacuation simulation models with different occupancy levels were constructed to compare evacuation time and safety margin before and after retrofit. The results are shown in Figure 25. After retrofit, the safety margin increases to 64 s, meeting the standard value and indicating that timely evacuation may be achievable. Overall, evacuation times decrease across all occupancy levels after retrofit, and the safe occupancy limit in terms of average number of residents per household increases from 3.5 to 4.5.

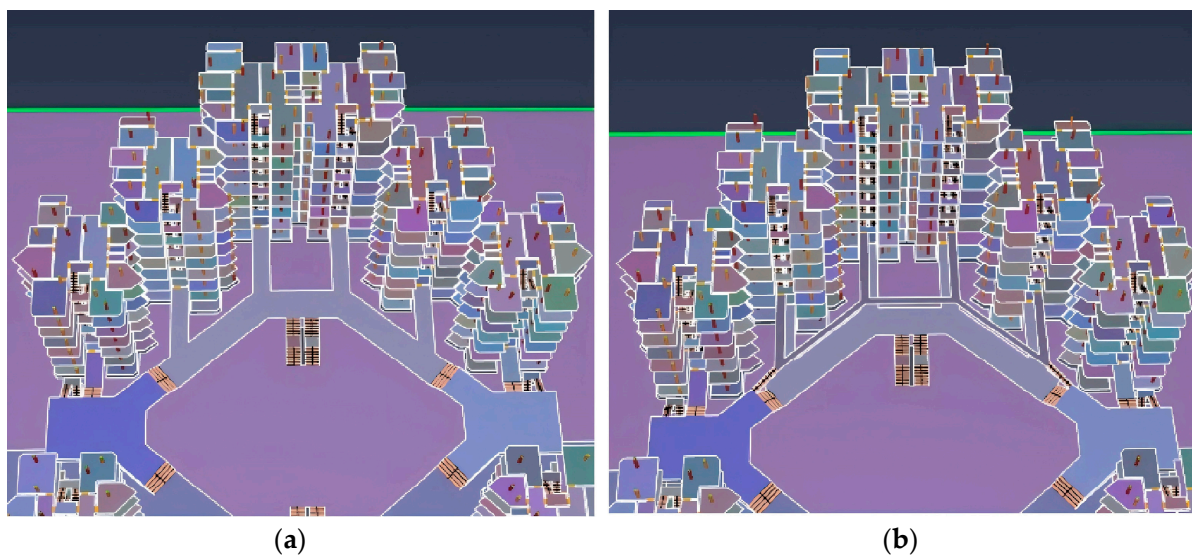


Figure 24. (a) Comparison before and (b) after adding evacuation platforms.

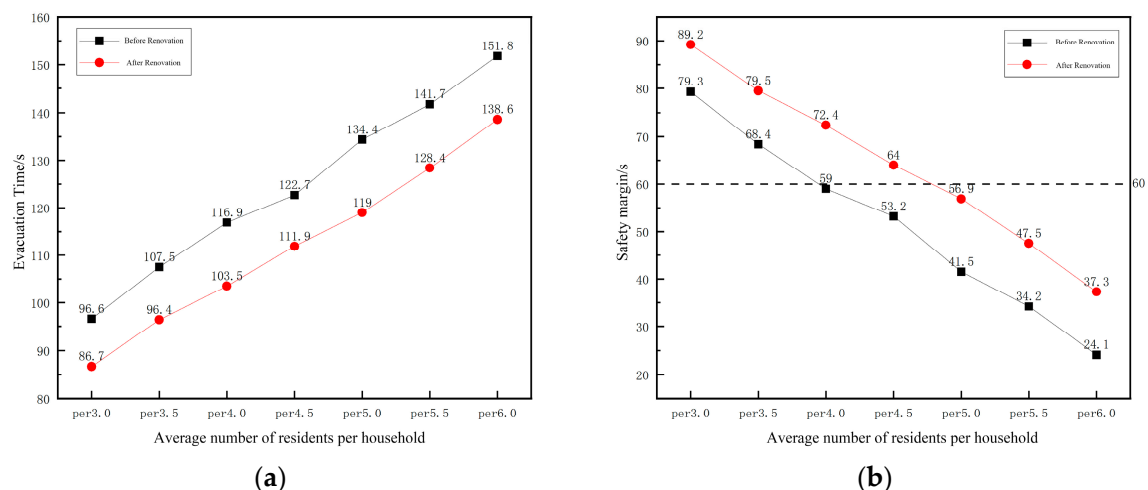


Figure 25. (a) Evacuation times and (b) safety margins before and after renovation.

5.3. Addition of Automatic Sprinkler Systems

A multi-level fire alarm and automatic sprinkler retrofit plan is also proposed for existing multi-story residential buildings. The plan includes the installation of smoke detectors in common areas and individual units, differential temperature heat sensors in high-risk areas such as kitchens and bedrooms, and manual alarm buttons at each floor exit. These systems are linked with automatic sprinklers and emergency lighting to support early detection and fire control. Given that the kitchen is the most frequent fire origin in residential units and that cost control is essential in existing building retrofits, sprinkler heads are installed only in the kitchen of each unit. Taking unit D as an example, a 74 °C temperature-sensitive automatic sprinkler system was installed above the ignition point in the kitchen, activating 3.4 s after fire ignition. Simulation results at 10-s intervals show that the sprinkler reduces the kitchen temperature from 300 °C to 170 °C by 175.6 s. The CO concentration shows no significant change at 172.6 s. At 185.9 s, the visibility slice shows that the area of stairwell coverage below the 5 m threshold is reduced compared with the case without sprinklers. Overall, the smoke concentration in the stairwell is reduced by the sprinkler system. Although coverage on the stairwell platform remains relatively high, coverage on the stair flight sections is reduced. The results are shown in Figures 26 and 27.

5.4. Limitations

Several limitations should be acknowledged. First, the fire simulations were conducted using a single mesh size of 0.2 m, and a formal grid convergence analysis was not performed. Although the selected mesh satisfied the FDS-recommended $D^*/\delta x$ criterion, additional mesh sensitivity studies may further improve confidence in the predicted hazard development times. Second, the Pathfinder evacuation model was adopted based on its extensively validated pedestrian movement algorithms. However, no project-specific calibration using measured evacuation data was available. The results should therefore be interpreted primarily as a comparative assessment of fire evacuation performance rather than an exact prediction of real-world evacuation behavior.

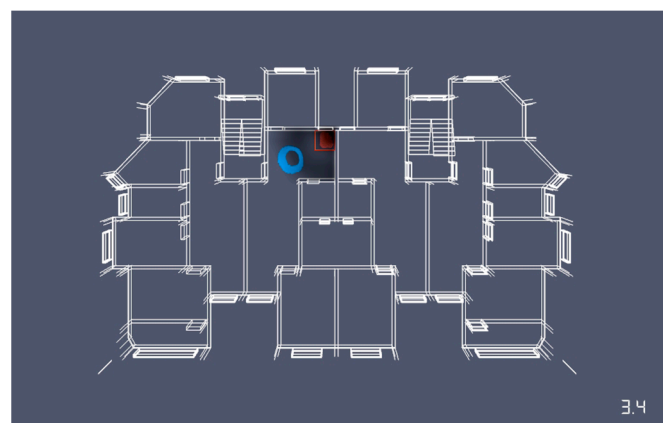


Figure 26. Addition of automatic sprinkler system and sprinkler activation time.

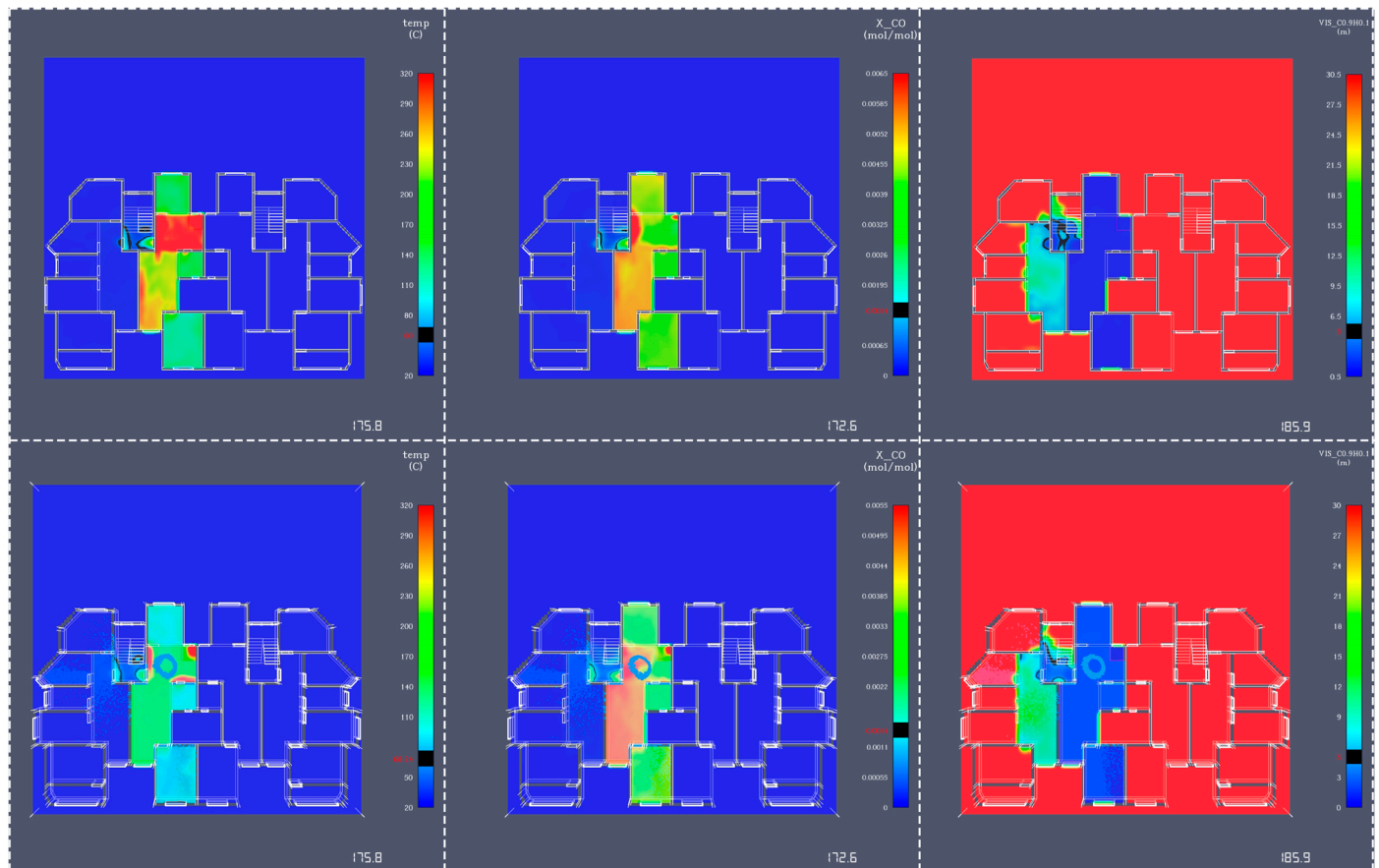


Figure 27. Effect of reducing the external platform width to 0.9 m.

6. Conclusions

A multi-factor coupling simulation framework integrating BIM, PyroSim, and Pathfinder was developed to investigate fire evacuation safety in existing multi-story residential buildings, using a typical residential cluster in Shenzhen as a case study. The main findings are as follows:

- (1) Kitchen location influences stairwell hazard severity. Layouts with kitchens farther from entrances (C and D) tend to show greater smoke temperature and visibility hazards ($D > C > A > B$), while the open kitchen design in Layout A promotes earlier smoke spread into stairwells. The alternating evacuation strategy may outperform uniform platform-based evacuation, particularly at higher occupant densities.
- (2) For the baseline nine-story buildings, the maximum safe occupancy is 3.5 persons per household. When the average exceeds 4.0 persons per household, the safety margin falls below 60 s. Concentrating slow-moving occupants on lower floors may improve overall evacuation efficiency, while counterflow and returning behaviors tend to cause the greatest obstruction on middle floors (5th–7th stories).
- (3) Multi-factor coupling analysis indicates that maximum safe occupancy tends to decrease with building height: approximately 6.0 persons per household for seven-story buildings, less than 5.0 for eight-story buildings, and less than 4.0 for nine-story buildings. Exit widths beyond 0.95 m yield diminishing returns, and critical stairwell obstacle sizes decrease from 0.6 m to 0.3 m as household density increases from 3.0 to 6.0 persons per household.

- (4) Three retrofit strategies were examined. Adding outdoor stairs achieved a safety margin of 71.2 s. Adding evacuation platforms raised the safe occupancy from 3.5 to 4.5 persons per household. Installing kitchen sprinklers reduced smoke concentrations in stairwell sections. These findings may offer a useful reference for fire safety retrofitting in existing multi-story residential buildings.
- (5) Several limitations should be noted. A formal grid convergence analysis was not conducted, and project-specific calibration for the evacuation model was not available. Future research may incorporate mesh sensitivity studies and real-world evacuation drills for validation.

Author Contributions: Q.Z.: conceptualization, funding acquisition, methodology, supervision, visualization, writing—original draft, writing—review and editing. C.L.: conceptualization, methodology, visualization, data curation, writing—original draft, writing—review and editing. Z.H.: conceptualization, methodology, data curation, visualization, writing—original draft. Y.F.: conceptualization, methodology, funding acquisition, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the National Key R&D Program of China (2024YFC3807900) and project of the State Key Laboratory of Subtropical Building and Urban Science (Grant No. 2025ZA03/2025ZB20).

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

FDS	Fire Dynamics Simulator
CFD	Computational Fluid Dynamics
BIM	Building Information Modeling
IFC	Industry Foundation Classes
MPI	Message Passing Interface

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