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Integrating Entropy Weight TOPSIS and BIM-Based Evacuation Simulation for Safety Assessment of High-Occupancy Buildings

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Abstract

Safe evacuation in high-occupancy buildings during extreme disaster events is a complex systems problem involving dynamic interactions among multiple factors. Conventional static evaluation methods, however, are limited in capturing the underlying evolution mechanisms. To address this gap, this study develops an integrated framework that combines static multi-criteria evaluation with dynamic evacuation simulation. From a “human–facility–environment” perspective, a multidimensional indicator system is established, encompassing building physical features, equipment configuration, and management performance. The entropy weight method is employed to objectively determine indicator weights, and the TOPSIS method is applied to conduct a comprehensive static assessment. On this basis, BIM and Pathfinder are used to perform microscopic evacuation simulations, and the dynamic performance data obtained are fed back into the evaluation system to verify and adjust the static results. The results show that dynamic simulation not only validates the reliability of the static evaluation but also uncovers nonlinear mechanisms and coupling effects among safety indicators during evacuation. By integrating digital simulation techniques with multi-criteria decision-making methods, this study improves the scientific rigor of safety evaluation and provides new insights for research and practice in building safety.

Keywords: high-occupancy buildings; evacuation safety; entropy weight method; TOPSIS; BIM; Pathfinder



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1. Introduction

In urban public spaces with high population density, efficient evacuation management is essential for ensuring life safety and enhancing urban resilience [1,2]. With rapid urbanization, the number of high-occupancy buildings—such as large shopping malls, metro stations, stadiums, hospital outpatient complexes, and school facilities—has increased substantially. Their spatial complexity, high occupant flow, and multifunctional use significantly amplify the challenges of evacuation management during extreme disaster events such as fires, earthquakes, and floods [3]. Disasters can not only cause structural damage and block evacuation routes but may also trigger cascading hazards, thereby posing severe challenges to both the efficiency and safety of evacuation [4–6].

Lessons learned from past incidents indicate that improper evacuation management—such as flawed route planning, disorganized guidance, or inadequate emergency facilities—often leads to casualties and chaos [7]. In addition, the unpredictability of individual behavior and irrational group responses under panic further increase uncertainty, making traditional experience-based management approaches inadequate [1]. Developing a scientific, multi-factor evaluation model is therefore of both theoretical and practical significance for optimizing evacuation strategies in high-occupancy buildings and strengthening urban disaster resilience.

Although multi-criteria decision-making (MCDM) methods such as Analytic Hierarchy Process (AHP), Data Envelopment Analysis (DEA), and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) have been applied to building safety evaluation, most studies still rely on static indicator systems and survey data [8,9]. While such methods allow for horizontal comparisons and rankings, they fail to reveal the complex interactions among spatial layouts, emergency facilities, and evacuees under dynamic and stochastic disaster conditions. A deeper understanding of how static evaluation results translate into dynamic evacuation performance remains lacking. For example, how the advantages of a high-scoring building manifest in evacuation dynamics, or how the weaknesses of a low-scoring system emerge as spatial bottlenecks and why. This gap in mechanistic understanding limits the practical utility of evaluation results for guiding evacuation optimization.

The maturity of Building Information Modeling (BIM) and microscopic evacuation simulation techniques offers new opportunities to address these limitations. BIM provides high-fidelity spatial and non-spatial data of buildings, forming a reliable digital foundation for evacuation analysis. Meanwhile, agent-based simulation tools such as Pathfinder enable modeling of individual and group movement and decision-making under emergency conditions, allowing for dynamic simulation and quantitative evaluation of evacuation processes [10,11]. Integrating these technologies into safety evaluation creates the potential to bridge static assessment and dynamic verification while uncovering underlying mechanisms. Recent studies have explored BIM-integrated frameworks for evacuation assessment in various emergency scenarios. One framework for high-rise buildings under post-earthquake fires highlighted the need for additional manual equipment, as conventional evacuation plans failed to address the effects of smoke and toxic gases [12]. Another study combined BIM with fire dynamics simulation and Pathfinder to assess evacuation performance, demonstrating the potential of BIM-driven simulations in improving fire safety management, especially in resource-constrained settings [13]. Additionally, a BIM-based evaluation framework that includes both physical and environmental factors showed how BIM can enhance fire safety performance [14]. These studies illustrate the value of BIM-based approaches for refining evacuation assessments and improving fire safety in buildings.

To overcome the disconnection between static evaluation and dynamic performance, this study proposes a hybrid method that combines entropy-weighted TOPSIS with BIM-based evacuation simulation. First, a static evaluation model is developed from a “human–facility–environment” perspective, establishing a multidimensional indicator system with objective weighting and ranking. Then, BIM and Pathfinder are used to embed static results into high-fidelity disaster scenarios for dynamic validation and in-depth analysis. Through comparative case studies, this research aims to achieve three contributions: (1) at the data level, verifying the correlation between static rankings and dynamic evacuation efficiency; (2) at the spatial level, transforming abstract indicator weaknesses into visualized spatial bottlenecks; and (3) at the systems level, revealing the interaction mechanisms among multidimensional indicators that shape evacuation performance. The proposed

“evaluation–verification” framework thus innovatively integrates static TOPSIS assessment with dynamic evacuation simulation, establishing a mapping between the two and providing a methodological foundation for precise evacuation optimization.

2. Related Work

2.1. Evacuation Planning and Design in High-Occupancy Buildings

For high-occupancy buildings such as large shopping malls, metro stations, stadiums, and schools, scientifically designed evacuation planning is critical to minimizing casualties and chaos during emergencies. In recent years, increasing attention has been given to the development of evacuation models, assessment methods, and safety management techniques tailored to such environments, with the aim of addressing the challenges arising from complex spatial configurations and diverse occupant characteristics. Effective evacuation planning must consider factors such as population density, building layout, multifunctional space design, and behavioral heterogeneity [8].

With technological advances, simulation-based analysis, real-time data monitoring, and intelligent surveillance systems have been increasingly integrated into evacuation research to improve the adaptability and responsiveness of evacuation plans [9–11]. Many studies emphasize the importance of explicitly defining exit routes, allocating fire protection facilities, and deploying emergency lighting during the design phase to ensure smooth evacuation [15,16]. Moreover, empirical research has demonstrated that the design of corridor widths, the number and distribution of exits, and vertical circulation routes such as stairways and emergency passages significantly affect evacuation efficiency and safety [17–19].

In disaster scenarios such as earthquakes, evacuation becomes even more challenging. Earthquakes not only pose structural risks that may block or collapse evacuation routes but also induce collective panic and confusion, seriously affecting evacuation performance. Unlike fire evacuation, earthquake evacuation requires rapid sheltering actions during seismic shaking, followed by structural safety assessment and re-evacuation planning [20]. Therefore, emergency planning for earthquake evacuation must integrate structural safety information, behavioral characteristics, and hazard dynamics, leading to multimodal evacuation strategies that enhance overall resilience.

2.2. Simulation and Modeling Approaches in Evacuation Research

Simulation modeling has become a critical tool for evaluating and optimizing evacuation management in high-occupancy buildings, as it enables the representation of complex factors such as individual behavior, crowd dynamics, and environmental conditions. Mainstream approaches include Agent-Based Modeling (ABM), Cellular Automata (CA), and Computational Fluid Dynamics (CFD) [21]. These techniques provide a means to capture dynamic movement and interactions during evacuation, thereby supporting evidence-based evacuation planning.

For example, Zheng et al. used PyroSim (for fire dynamics) and Pathfinder (for evacuation) to model a large commercial complex and analyze visibility, temperature, and CO concentration under different smoke exhaust conditions [6,22]. Rahmani et al. applied CFD simulations to a super high-rise hospital, showing that smoke spread and heat release escalate rapidly, creating significant risks [23]. Their study highlighted the importance of fire safety measures, including modifications to stairwells and elevator shafts, as well as improvements in smoke control systems, fire alarms, and extinguishers.

Nevertheless, simulation-based research requires substantial data on building layout, occupant behavior, and emergency scenarios, which may be difficult to obtain. In addition,

these models are often computationally intensive and may not be readily applicable in ordinary high-occupancy buildings without simplification.

2.3. Safety and Risk Management Evaluation Method

In the safety and risk management of high-occupancy buildings, Multi-Criteria Decision Analysis (MCDA) techniques are widely used to evaluate the effectiveness of evacuation strategies and safety measures under extreme events. Common approaches include Analytic Hierarchy Process (AHP), fuzzy logic, Data Envelopment Analysis (DEA), and the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) [24].

AHP is frequently adopted due to its hierarchical structure and simplicity, particularly when integrating expert judgment and qualitative assessments [25,26]. However, AHP is highly dependent on subjective inputs and may be biased, limiting objectivity. DEA emphasizes efficiency assessment and has been applied to quantify safety management efficiency in large-scale public buildings, particularly when input–output relationships are the focus [27]. Yet, DEA is less effective in incorporating dynamic human behavior and uncertainty.

TOPSIS has recently gained increasing popularity because it can integrate objective weights with decision-makers' preferences and is well-suited to multi-indicator comparisons under uncertain conditions [28,29]. Studies have shown that TOPSIS is effective in evaluating evacuation strategies in disaster scenarios, assisting decision-makers in selecting optimal plans in complex and variable environments [30]. Moreover, hybrid approaches that combine entropy weighting with TOPSIS enhance objectivity and reliability, offering strong decision support for evacuation management in high-occupancy buildings.

2.4. Integration of BIM and Microscopic Simulation in Evacuation Research

BIM, as a digital representation containing both geometric and non-geometric data, provides a high-fidelity spatial foundation for evacuation research [31]. BIM not only describes building components with high precision but also integrates equipment and material properties, thereby supporting structural performance analysis and evacuation planning under disaster conditions [32].

Recent years have seen increasing integration of BIM with microscopic evacuation simulation tools such as Pathfinder and AnyLogic. These agent-based platforms can simulate individual and group movement, decision-making, and interactions in emergencies, outputting dynamic data such as evacuation time, density distribution, and congestion hotspots [33]. For instance, Ruppel et al. developed a BIM-based game platform for fire evacuation simulation [34], while Choi et al. designed a BIM-driven evacuation management inspection system for complex high-rise buildings [35]. Similarly, Bi conducted research on BIM-based fire emergency planning at Beijing University of Civil Engineering and Architecture [36], and He applied BIM in evacuation research at an exhibition center to support performance-based evacuation design [6].

The research trend is shifting from single-scenario simulations toward integrated analysis that combines simulation with evaluation frameworks. For example, Han et al. used Pathfinder to simulate and compare different evacuation strategies in a shopping mall [37]. However, most existing studies focus on scheme comparison or visualization, with limited work on using simulation results as validation and mechanism analysis tools within multi-indicator evaluation systems. Integrating entropy-weighted TOPSIS with BIM–Pathfinder simulation offers a promising pathway to not only compare alternative evacuation strategies but also to uncover underlying mechanisms and optimization opportunities, thus enhancing both analytical depth and practical applicability.

3. Materials and Methods

3.1. Indicator System

To comprehensively assess the effectiveness of evacuation management in high-occupancy buildings, a systematic evaluation indicator system was established, covering building design, facility configuration, personnel and management, emergency efficiency, and technological support. The structure of the evaluation system is shown in Table 1.

Table 1. Evaluation indicator system for the effectiveness of evacuation management in high-occupancy building.

Level 1	Level 2	Level 3
Effectiveness of Safety Evacuation Management Models for High-Occupancy Buildings	Building Scale (A)	Building area (A1)
		Number of floors (A2)
		Occupant capacity (A3)
	Design and Layout (B)	Average width of evacuation routes (B1)
		Total area of evacuation routes (B2)
		Number and distribution of exits (B3)
		Vertical evacuation capacity (B4)
		Proportion of unobstructed evacuation routes (B5)
		Average evacuation distance from key areas (B6)
	Emergency Facilities (C)	Completeness of emergency lighting (C1)
		Duration of emergency lighting (C2)
		Proportion of functioning evacuation signs (C3)
		Number and distribution of extinguishers (C4)
		Number of fire hydrants (C5)
		Coverage of sprinkler system (C6)
		Availability of emergency medical equipment (C7)
		Annual expenditure on equipment maintenance (C8)
	Personnel and Emergency Management (D)	Occupant density (D1)
		Security staff allocation (D2)
		Qualification rate of security staff training (D3)
		Qualification rate of general staff training (D4)
		Frequency of evacuation drills (D5)
		Expenditure on staff training (D6)
	Evacuation Efficiency and Safety (E)	Evacuation time (E1)
		Emergency response time (E2)
Recovery time after evacuation (E3)		
Number of incidents per year (E4)		
Information Management and Technical Support (F)	Effectiveness of emergency communication system (F1)	
	Coverage of intelligent surveillance system (F2)	
	Proportion of real-time personnel tracking (F3)	
	Frequency of evacuation simulation use (F4)	
	Degree of integration of emergency systems (F5)	

3.2. Determination of Indicator Values

Before conducting the evaluation, it is necessary to collect data for each indicator listed in Table 1. During data acquisition, both timeliness and comprehensiveness must be ensured. The determination or calculation methods for each indicator are as follows:

- (1) Building area (A1), unit: m^2 . The total floor area of the high-occupancy building, reflecting its overall scale. This can be obtained from architectural drawings or verified on-site.
- (2) Number of floors (A2). Represents the total number of floors in the building, as greater height generally increases the complexity of vertical evacuation. This can be confirmed through design documents or field inspection.
- (3) Occupant capacity (A3). The maximum number of people the building can accommodate, serving as a key reference for evacuation demand. Determined from architectural design documents.
- (4) Average width of evacuation routes (B1), unit: m. Measure the widths of all evacuation routes (corridors, stairways, etc.) and calculate the average.
- (5) Total area of evacuation routes (B2), unit: m^2 . The sum of the floor areas of all evacuation passages, including corridors, stairways, and other designated routes.
- (6) Number of exits (B3), unit: exits per 1000 occupants. Based on the building design, calculate the number of exits provided per 1000 occupants. Building codes generally require at least two exits per floor and per 1000 occupants. The result should meet or exceed local code requirements.
- (7) Vertical evacuation capacity (B4), unit: persons/min. The evacuation throughput of vertical routes (elevators, stairways). Calculated based on the number and size of elevators/stairs and the number of people they can evacuate per minute.
- (8) Proportion of unobstructed evacuation routes (B5), unit: %. Inspect all evacuation passages for obstructions (e.g., medical devices, furniture) and calculate the proportion of unobstructed routes.
- (9) Average evacuation distance from key areas (B6), unit: m. Measure the distances from key areas (e.g., high-density spaces or areas with mobility-impaired occupants) to the nearest exits and compute the average.
- (10) Completeness of emergency lighting (C1), unit: %. Check all emergency lighting fixtures and calculate the proportion functioning properly.
- (11) Duration of emergency lighting (C2), unit: hours. Measure how long the emergency lighting system can operate during a power outage.
- (12) Proportion of functioning evacuation signs (C3), unit: %. Inspect evacuation signage and calculate the percentage that is clearly visible and functional under emergency conditions.
- (13) Number and distribution of fire extinguishers (C4), unit: units/1000 m^2 . Record the number and distribution of extinguishers within the building, which should meet design standards relative to floor area.
- (14) Number of fire hydrants (C5). Count the hydrants on each floor, ensuring that each hydrant provides adequate water pressure for firefighting.
- (15) Coverage of sprinkler system (C6), unit: m^2 . Assess the coverage area of the sprinkler system, ensuring all high-risk areas are included.
- (16) Availability of emergency medical equipment (C7), unit: %. Check the availability of medical equipment (e.g., stretchers, oxygen tanks) and calculate the percentage available relative to requirements.
- (17) Annual expenditure on equipment maintenance (C8), unit: CNY. The yearly cost for repairing and replacing safety equipment, including fire protection systems, emergency evacuation tools, and personal protective equipment.

- (18) Occupant density (D1), unit: persons/m². Measure occupant density across different building areas, especially in crowded spaces such as waiting rooms or diagnostic areas. Multiple measurements at different times can be averaged.
- (19) Security staff allocation (D2), unit: persons/100 staff. The number of security personnel per 100 building staff.
- (20) Qualification rate of security staff training (D3), unit: %. Review security staff training records to determine the proportion who have passed emergency management and evacuation training.
- (21) Qualification rate of general staff training (D4), unit: %. Review general staff evacuation training records to determine the proportion who passed.
- (22) Frequency of evacuation drills (D5), unit: drills per year. Determined by the number of evacuation exercises conducted annually.
- (23) Expenditure on staff training (D6), unit: CNY. Annual investment in staff training, especially for safety and emergency personnel, including courses, certifications, and exercises.
- (24) Evacuation time (E1), unit: min. Obtained through BIM-based microscopic evacuation simulation. High-fidelity simulation data objectively reflect evacuation performance, avoiding subjective bias and ensuring close linkage to building physical characteristics.
- (25) Emergency response time (E2), unit: min. The time between the onset of an emergency and the initiation of emergency response procedures.
- (26) Recovery time after evacuation (E3), unit: hours. The time required for the building to resume normal operations after evacuation is completed.
- (27) Number of incidents (E4), unit: events/year. Count the number of incidents threatening occupant safety (e.g., fires, accidents) that occurred in the previous year.
- (28) Effectiveness of emergency communication system (F1), unit: %. Evaluate the coverage of the emergency communication system (e.g., speakers, alarms, digital displays) as a proportion of total building area.
- (29) Coverage of intelligent surveillance system (F2), unit: %. Assess the coverage of surveillance systems (e.g., video monitoring, tracking) across key areas such as entrances, evacuation routes, waiting zones, and corridors.
- (30) Proportion of real-time personnel tracking (F3), unit: %. The proportion of priority populations (e.g., vulnerable groups) tracked using real-time positioning technologies.
- (31) Frequency of evacuation simulation use (F4), unit: times/year. The frequency with which evacuation simulation systems are applied to evaluate and optimize evacuation plans.
- (32) Degree of emergency system integration (F5), unit: %. The percentage of integration between the emergency communication system and other critical systems (e.g., fire alarms, building automation, information systems, access control, staff notification systems).

3.3. Calculation Process

The evaluation of evacuation patterns in high-occupancy buildings using the entropy weight method and the TOPSIS model follows this rationale: first, the entropy weight method is applied to determine the weights of each indicator according to their relative importance. Then, the standardized indicator data and corresponding weights are incorporated into the TOPSIS model to calculate the comprehensive safety scores of the buildings. Finally, the rankings of evacuation patterns are obtained. Although AHP is widely applied in safety evaluation research as a structured expert-judgment approach, it is inherently semi-quantitative and may introduce subjectivity. In this study, AHP is mentioned only as a theoretical reference; the actual indicator weighting adopts the en-

tropy weight method, which determines weights objectively based on data variability and minimizes subjective bias. This makes entropy-based weighting more appropriate for the proposed evaluation–simulation feedback framework. The detailed calculation process is as follows:

Step 1: Assume that m high-occupancy buildings with comparable conditions are to be evaluated using n indicators. An initial decision matrix $A = (a_{ij})_{m \times n}$ is constructed, where a_{ij} represents the value of the j -th indicator of the i -th building ($i = 1, 2, \dots, m; j = 1, 2, \dots, n$).

Step 2: Normalize the initial decision matrix to obtain the standardized matrix $R = (r_{ij})_{m \times n}$. For positive indicators (the higher, the better), normalization is performed using Equation (1)

$$r_{ij} = \frac{a_{ij} - \min_j a_{ij}}{\max_j a_{ij} - \min_j a_{ij}} \tag{1}$$

For negative indicators (the lower, the better), normalization is performed using Equation (2):

$$r_{ij} = \frac{\max_j a_{ij} - a_{ij}}{\max_j a_{ij} - \min_j a_{ij}} \tag{2}$$

For indicators whose optimal value is neither maximized nor minimized, normalization can be performed using Equations (3) and (4).

$$M = \max (|a_{ij} - a_{best}|) \tag{3}$$

$$r_{ij} = 1 - \frac{|a_{ij} - a_{best}|}{M} \tag{4}$$

Step 3: Calculate the entropy value of each indicator using Equation (5):

$$H_j = -\frac{1}{\ln m} \sum_{i=1}^m f_{ij} \ln f_{ij} \tag{5}$$

where $f_{ij} = \frac{r_{ij}}{\sum_{i=1}^m r_{ij}}$. If $f_{ij} = 0$, then $f_{ij} \ln f_{ij} = 0$.

Step 4: Calculate the entropy weight of each indicator using Equation (6):

$$\omega_i = \frac{1 - H_j}{n - \sum_{j=1}^n H_j}, 0 \leq \omega_j \ll 1, \sum_{j=1}^n \omega_j = 1 \tag{6}$$

Step 5: Multiply the standardized matrix $R = (r_{ij})_{m \times n}$ by the weights obtained through the entropy method to yield the weighted standardized matrix $Y = (y_{ij})_{m \times n}$:

$$y_{ij} = r_{ij} \times \omega_j \tag{7}$$

Step 6: Determine the positive ideal solution and the negative ideal solution. For the weighted standardized matrix, the maximum value of positive indicators and the minimum value of negative indicators constitute the positive ideal solution (Equation (8)), while the minimum value of positive indicators and the maximum value of negative indicators constitute the negative ideal solution (Equation (9)).

$$Z^+ = \left(\max_{1 \leq i \leq m} y_{ij} \mid j \in j^+, \min_{1 \leq i \leq m} y_{ij} \mid j \in j^- \right) = (Z_1^+, Z_2^+, \dots, Z_n^+) \tag{8}$$

$$Z^- = \left(\min_{1 \leq i \leq m} y_{ij} \mid j \in j^+, \max_{1 \leq i \leq m} y_{ij} \mid j \in j^- \right) = (Z_1^-, Z_2^-, \dots, Z_n^-) \quad (9)$$

Step 7: Calculate the Euclidean distance of each building from the positive and negative ideal solutions using Equations (10) and (11):

$$D_i^+ = \sqrt{\sum_{j=1}^n (y_{ij} - z_j^+)^2} \quad (i = 1, 2, \dots, m) \quad (10)$$

$$D_i^- = \sqrt{\sum_{j=1}^n (y_{ij} - z_j^-)^2} \quad (i = 1, 2, \dots, m) \quad (11)$$

Step 8: Calculate the relative closeness of each building to the positive ideal solution using Equation (12):

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (12)$$

The value of C_i lies between 0 and 1. The closer it is to 1, the more the evacuation management model of the building approaches the positive ideal solution.

3.4. Evacuation Simulation Validation Based on BIM and Pathfinder

To dynamically validate the static evaluation model and conduct an in-depth mechanism analysis, this study develops an integrated analysis process based on BIM and the Pathfinder microscopic simulation software [37]. The purpose of this process is to place the static evaluation results into high-fidelity virtual disaster scenarios, thereby testing their validity and revealing the underlying mechanisms that affect evacuation performance.

First, the BIM models were reconstructed. Based on the results of the static evaluation, representative case studies were selected, such as the top-ranked Hospital A and the lowest-ranked Hospital D. According to their architectural design drawings, high-precision three-dimensional BIM models were built using professional software such as Revit. These models included the complete building structure, door and window layout, evacuation stairways, and the locations of critical emergency facilities, thus providing a realistic and reliable digital spatial environment for subsequent simulations.

Second, the simulation parameters were configured. The BIM models were imported into the Pathfinder simulation environment, and parameters were set according to the characteristics of hospital outpatient populations. Specifically, different categories of occupants were defined, such as medical staff (with relatively higher mobility), general patients, and mobility-impaired patients (such as those using wheelchairs, with lower mobility). Reasonable proportions were assigned to each category, and their initial positions were randomly distributed across functional areas such as waiting zones, consulting rooms, and pharmacies, in order to reflect realistic occupancy conditions.

On this basis, disturbance scenarios were introduced to test the robustness of the evacuation system. To better approximate real disaster conditions, the simulation incorporated localized structural damage, such as randomly closing a major exit or blocking a stairway, so as to evaluate the emergency performance of the building under non-ideal conditions.

After the simulation was executed, the system generated multiple key outputs for comprehensive validation and analysis. These outputs mainly included the total evacuation time and the duration of different evacuation stages, which directly correspond to and verify the static evaluation indicator “evacuation time (E1)”. The indicator system in Table 1 focuses on intrinsic building and management conditions that reflect baseline evacuation capability. Scenario-specific variables (e.g., hazard type and location) are not included at this stage, as they vary across incident conditions and are incorporated instead

through dynamic simulation analysis. Evacuation time derived from the BIM-Pathfinder simulation is subsequently introduced as E1 to calibrate and verify the static evaluation, forming a closed-loop static-to-dynamic validation process. They also included occupant movement trajectories and density maps, which were used to visualize congestion points and bottleneck areas, thereby validating the indicators related to “evacuation route design (B-type)”. The utilization rates and real-time flow curves of different exits were also obtained to analyze the balance and efficiency of exit use, corresponding to the indicator “number and distribution of exits (B3)”. Furthermore, targeted analyses of evacuation routes for specific populations such as mobility-impaired occupants were carried out, providing additional evaluation of the applicability and fairness of evacuation strategies across different groups. Through these multidimensional simulation outputs, this study achieves comprehensive validation and in-depth analysis of the evaluation model, ranging from macro-level efficiency to micro-level mechanisms.

4. Results

4.1. Case Description and Input Indicators

To verify the effectiveness of the proposed evaluation model, eight hospitals were selected, and data regarding building design, emergency facilities, personnel training, and evacuation performance were collected according to the indicator acquisition methods described in Section 3.2, which were collected through multiple channels, including field surveys, structured interviews with hospital emergency management and facility operation personnel, on-site measurements of evacuation features (e.g., corridor widths, exit counts), and review of architectural construction drawings and internal facility management records. The hospitals included in this study vary in scale, with gross floor areas ranging from 3000 to 10,000 m² and building heights from 3 to 10 floors. Functional areas include outpatient diagnosis and treatment rooms, emergency departments, imaging and laboratory facilities, and public waiting zones, as shown in Figure 1. The peak occupancy for each hospital ranged between 600 and 1200 people during busy outpatient periods. Major evacuation routes consist of public corridors, stairwells, and multiple exit points, complemented by emergency lighting and fire-protection equipment. These characteristics reflect typical large public medical facilities in China and provide a representative context for evaluating the proposed assessment framework. Therefore, eight hospitals were selected to ensure diversity in scale, spatial layout, and operational conditions while maintaining the feasibility of BIM modeling and simulation workloads. This sample size provides sufficient variability to validate the robustness of the proposed framework across different hospital types within the same regional system, while avoiding excessive computational and data-collection burden.

To reflect the corrective effect of dynamic simulation on static evaluation, a stepwise assessment approach was adopted in this study: first, an initial evaluation was conducted based on static attributes such as building design, facility configuration, and management level (excluding the evacuation time indicator E1); subsequently, the results were adjusted using actual evacuation time data obtained from BIM simulations. The values of each indicator are presented in Table 2.

Table 2. Indicator Values of Outpatient Buildings in Eight Hospitals.

No.	Indicator	A	B	C	D	E	F	G	H
1	Building Area (A1)	5000	8000	6000	4000	7000	3000	9000	10,000
2	Number of Floors (A2)	5	8	6	4	7	3	9	10
3	Waiting Area Capacity (A3)	300	500	350	250	450	200	600	700
4	Average Width of Evacuation Routes (B1)	2	2.5	2.2	1.8	2.4	1.5	2.7	3
5	Total Area of Evacuation Routes (B2)	600	900	750	550	850	450	1000	1100
6	Number of Exits (B3)	2.0	2.5	2.2	1.8	2.4	1.5	2.7	3.0
7	Vertical Evacuation Capacity (B4)	100	120	110	90	115	80	130	140
8	Evacuation Route Clearance Ratio (B5)	90%	95%	92%	85%	94%	80%	96%	98%
9	Average Evacuation Distance in Key Areas (B6)	20	15	18	22	17	25	14	12
10	Completeness of Emergency Lighting (C1)	95%	98%	96%	90%	97%	88%	99%	100%
11	Duration of Emergency Lighting (C2)	3	4	3.5	2.5	3.8	2	4.5	5
12	Proportion of Functional Evacuation Signage (C3)	90%	95%	92%	88%	93%	85%	97%	99%
13	Number and Distribution of Fire Extinguishers (C4)	10	12	11	9	12	8	13	14
14	Number of Fire Hydrants (C5)	3	3.5	3.2	2.8	3.3	2.5	3.7	4
15	Coverage of Sprinkler Fire Suppression Systems (C6)	600	850	700	500	780	400	400	900
16	Availability Percentage of First-Aid Equipment (C7)	85%	90%	87%	80%	88%	75%	92%	95%
17	Annual Maintenance Expenditure for Equipment (C8)	10,000	15,000	12,000	9000	13,000	8500	16,000	18,000
18	Personnel Density (D1)	1.5	2	1.8	1.2	1.9	1	2.2	2.5
19	Security Staff Deployment (D2)	3	4	4	3	4	2	4	5
20	Pass Rate of Security Personnel Training (D3)	85%	90%	88%	80%	89%	78%	92%	95%
21	Personnel Training Pass Rate (D4)	90%	92%	91%	85%	91%	83%	94%	96%
22	Frequency of Evacuation Drills (D5)	6	8	7	5	7	4	9	10
23	Expenditure on Personnel Training (D6)	800	750	780	820	770	840	720	700
24	Emergency Response Time (E2)	5	6	5.5	6.5	5.2	7	4.8	4.5
25	Post-Evacuation Recovery Time (E3)	1	2	1.5	2.5	1.8	3	1.2	1
26	Number of Incidents (E4)	90%	95%	93%	88%	94%	85%	97%	90%
27	Effectiveness of Emergency Communication Systems (F1)	85%	88%	86%	80%	87%	78%	90%	92%
28	Coverage of Intelligent Monitoring Systems (F2)	80%	85%	82%	75%	83%	72%	88%	90%
29	Real-Time Personnel Positioning Technology (F3)	5	6	5.5	4	5.8	3	7	8
30	Usage Frequency of Evacuation Simulation Systems (F4)	80%	85%	82%	75%	83%	70%	88%	90%
31	Integration Level of Emergency Systems (F5)	65%	60%	85%	70%	75%	60%	85%	95%



Figure 1. Hospital outpatient complex as a typical high-occupancy building (photo by authors).

4.2. Evaluation and Analysis of Safety Evacuation Model Based on Static Indicators

Following the calculation methods outlined in Section 3.3, the personnel safety evacuation management levels of the eight hospitals were computed and evaluated using the entropy weight method combined with the TOPSIS method. First, the hospital indicator data were standardized to ensure comparability across the same scale. Then, the entropy weights of each indicator were calculated to determine their relative importance, and a weighted standardized matrix was constructed for further analysis. Subsequently, the Euclidean distances of each hospital to the ideal and anti-ideal solutions were calculated, and the hospitals were ranked according to their relative closeness. The results are summarized in Table 3.

Table 3. Evaluation Results of Safety Evacuation Plans for Eight Outpatient Buildings.

Building	Euclidean Distances		Relative Closeness	Ranking
	Euclidean Distance to Positive Ideal Solution	Euclidean Distance to Negative Ideal Solution		
A	0.12181	0.078	0.39102	6
B	0.07164	0.134	0.65080	3
C	0.09389	0.103	0.52232	5
D	0.15044	0.059	0.28323	7
E	0.08039	0.117	0.59248	4
F	0.18470	0.059	0.24252	8
G	0.07244	0.154	0.67959	2
H	0.06092	0.190	0.75730	1

The results indicate that Hospital H has the highest personnel safety evacuation management level, excelling across all indicators, including building scale, evacuation passage design, emergency facility configuration, and personnel training. As the hospital with the highest current management level, its practices and management system can serve as a reference or guideline for optimizing management strategies in other outpatient buildings with similar conditions, thereby improving their overall management quality.

4.3. BIM-Pathfinder-Based Evacuation Simulation

To explore the intrinsic dynamic mechanisms underlying the static evaluation results, Hospitals A and D were selected as representative cases for comparative BIM-Pathfinder evacuation simulation. Hospitals A and D were selected as representative cases due to their significantly different rankings in the static entropy–TOPSIS assessment and their distinct architectural and operational characteristics. Hospital A performed relatively well in the baseline evaluation, whereas Hospital D ranked lower, enabling a clear contrast in

simulation outcomes. This selection strategy allows for more meaningful demonstration of the framework's ability to validate and calibrate TOPSIS assessment results through evacuation simulation.

Figure 2 shows the constructed hospital BIM information model. The BIM models were created in Autodesk Revit based on architectural construction drawings and verified through on-site measurements. To support interoperability, an openBIM workflow was adopted: models were exported in the Industry Foundation Classes (IFC) format and imported into Pathfinder for evacuation simulation. The geometric model included corridors, stairwells, exit doors, and room boundaries. Simulation parameters were configured in Pathfinder, including agent categories, movement speed distributions, initial occupant distribution by floor, pre-evacuation delay settings, and constraints on door and stair capacities, alongside path-selection rules to reflect realistic evacuation behavior. Figure 3 presents the evacuation simulation model imported into Pathfinder and depicts the initial distribution of personnel at the start of the simulation.

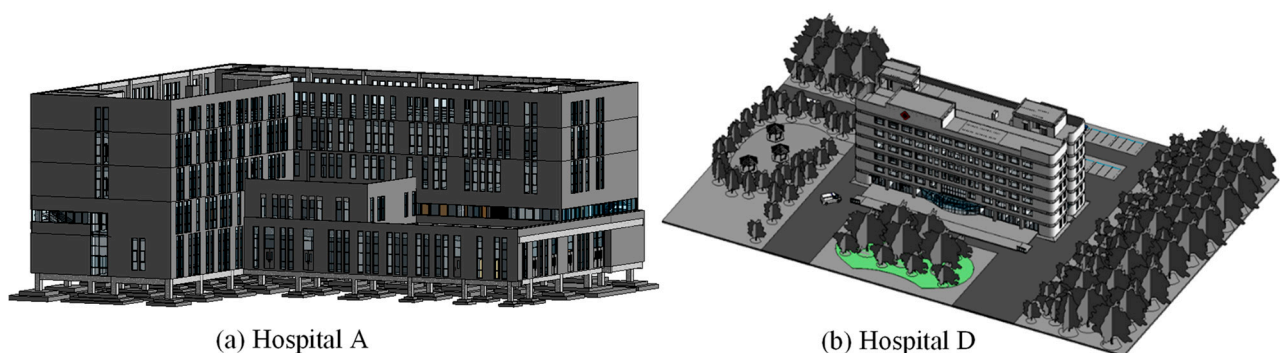


Figure 2. BIM Models. (a) Hospital A. (b) Hospital D.

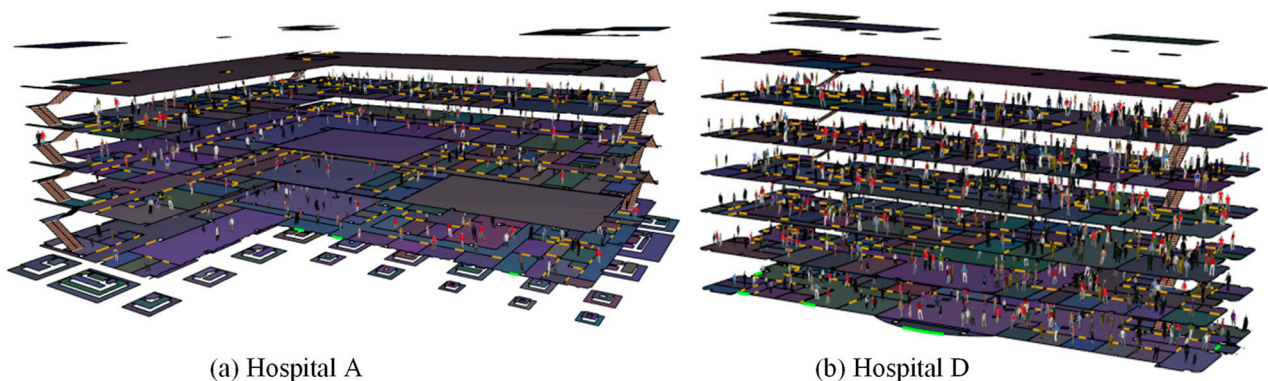


Figure 3. Evacuation Models. (a) Hospital A. (b) Hospital D.

To accurately simulate evacuation behavior of various personnel types in the hospital scenario, detailed personnel parameters were set based on on-site surveys and relevant literature [1,38–40]. Walking speed parameters were differentiated according to professional roles and physical conditions: medical staff (e.g., doctors and nurses), familiar with the environment and agile, were assigned relatively higher speeds (means of 0.90 m/s and 1.00 m/s, respectively); administrative and support staff were assigned medium speeds (means of 0.85 m/s and 0.95 m/s); patients were further categorized by mobility: self-moving patients at 0.85 m/s, moderate-condition patients assisted by one person at 0.45 m/s (with the assistant moving at 0.9 m/s, maximum cooperation distance 0.5 m), and severe-condition patients assisted by two people at 0.10 m/s (team moving at 0.5 m/s, maximum cooperation distance 1 m). All personnel speeds fluctuated around the mean following a normal

distribution to reflect individual variability. In addition, the initial number of personnel on different floors and functional zones (e.g., F1–F4 outpatient areas, F1–F6 inpatient areas) was precisely assigned according to actual survey data, ensuring that the simulation scenario realistically represented personnel composition, cooperation relationships, and spatial distribution, thus providing a reliable basis for subsequent dynamic evacuation analysis, as shown in Tables 4–6 and Figure 4.

Table 4. Walking Speed Parameters for Different Personnel Types (Unit: m/s).

Personnel Type	Range (m/s)	Mean (m/s)	Standard Deviation (m/s)
Doctor	0.70–1.10	0.90	0.14
Nurse	0.80–1.20	1.00	0.15
Administrative Staff	0.65–1.05	0.85	0.13
Support Staff	0.85–1.25	1.05	0.16
Logistics Staff	0.75–1.15	0.95	0.14
Patient (Self-Mobile)	0.65–1.05	0.85	0.13
Patient (Moderate)	0.35–0.55	0.45	0.07
Patient (Severe)	0.05–0.15	0.10	0.03
Family Members	0.60–1.20	0.95	0.18

Table 5. Initial Distribution of Personnel by Floor in Hospital A (Unit: Persons).

Personnel Type	F1	F2	F3	F4
Doctor	20	25	15	10
Nurse	35	37	30	40
Administrative Staff	15	8	6	5
Support Staff	8	8	4	5
Logistics Staff	6	6	6	6
Patient (Self-Mobile)	60	23	15	10
Patient (Moderate)	0	10	20	20
Patient (Severe)	0	5	5	10
Family Members	40	30	40	30

Table 6. Initial Distribution of Personnel by Floor in Hospital D (Unit: Persons).

Personnel Type	F1	F2	F3	F4	F5	F6
Doctor	20	25	30	30	30	25
Nurse	35	35	35	35	35	30
Administrative Staff	10	8	8	8	8	8
Support Staff	5	5	5	5	5	5
Logistics Staff	5	5	5	5	5	5
Patient (Self-Mobile)	40	25	25	20	15	15
Patient (Moderate)	0	10	20	10	20	20
Patient (Severe)	0	5	5	10	15	15
Family Members	30	30	25	30	30	30

During the simulation, secondary obstacles simulating fire scenarios were introduced, as shown in Figure 5, including areas with high temperatures, combustible materials burning, or regions releasing pungent odors, which further influenced personnel flow. Figures 6 and 7 capture the evacuation status of each floor at different time points. The simulation assumes non-structural obstruction caused by fire hazards, representing realistic hospital evacuation conditions during a fire emergency under code-compliant design. While this study focuses on fire evacuation, the proposed framework is hazard-independent and may be extended to other emergency scenarios in future work by incorporating smoke, heat, and toxicity-related parameters.

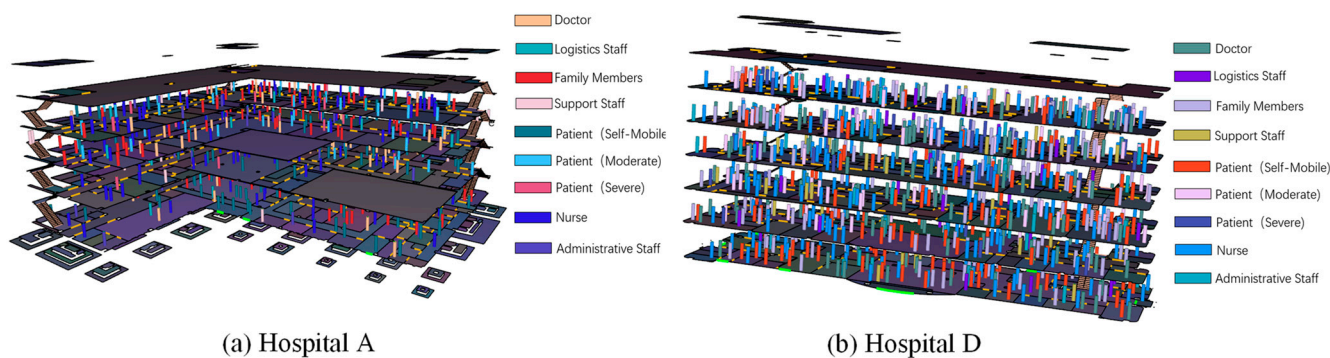


Figure 4. Illustration of Personnel Distribution. (a) Hospital A. (b) Hospital D.

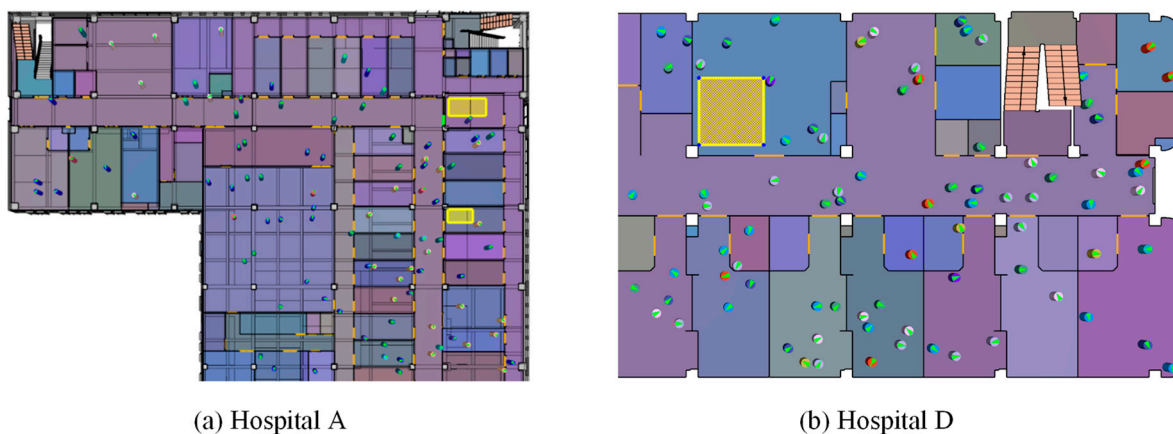


Figure 5. Obstacle Areas (Fire-induced obstruction: Areas in the west wing corridor with high temperatures and burning materials, rendering the area impassable; areas in the central storage room releasing pungent odors.). (a) Hospital A. (b) Hospital D.

To analyze the dynamic processes and spatial mechanisms contributing to differences in evacuation time, the flow characteristics of personnel through key building nodes were examined. The time-series curves of exit flow generated from the simulation (Figures 8 and 9) visually depict the dynamic features of personnel movement. The curves show a typical “rapid rise—peak maintenance—gradual decline” pattern, fully reflecting the process from congregation to transit and dispersal. Comparing the flow curves of the two hospitals reveals that Hospital A’s multiple exits have highly overlapping peak flows with balanced values, indicating effective crowd diversion, whereas Hospital D’s flow is heavily concentrated at a single main exit, with a significantly higher and prolonged peak, highlighting persistent congestion bottlenecks. These findings provide direct data support for subsequent congestion localization and mechanism analysis.

Simulation results (Table 7) show that Hospital A is significantly more efficient than Hospital D in evacuation. Specifically, Hospital A completed full personnel evacuation in 598.3 s (approximately 9 min 58 s), saving 91.7 s ($\approx 13.3\%$ improvement) compared with Hospital D (690 s, 11 min 30 s). This difference is more pronounced at the tail end of the evacuation process, with the last person evacuated from Hospital A at 625.4 s versus 735.2 s for Hospital D, indicating superior evacuation organization efficiency. From a spatial utilization perspective, significant differences exist: Hospital D experiences severe congestion at the main corridor–stair junction (peak density 1.78 persons/m²), whereas the maximum congestion in Hospital A is only 1.99 persons/m². Exit usage analysis shows more balanced use in Hospital A, while Hospital D overly relies on the main exit, resulting in persistent bottlenecks.

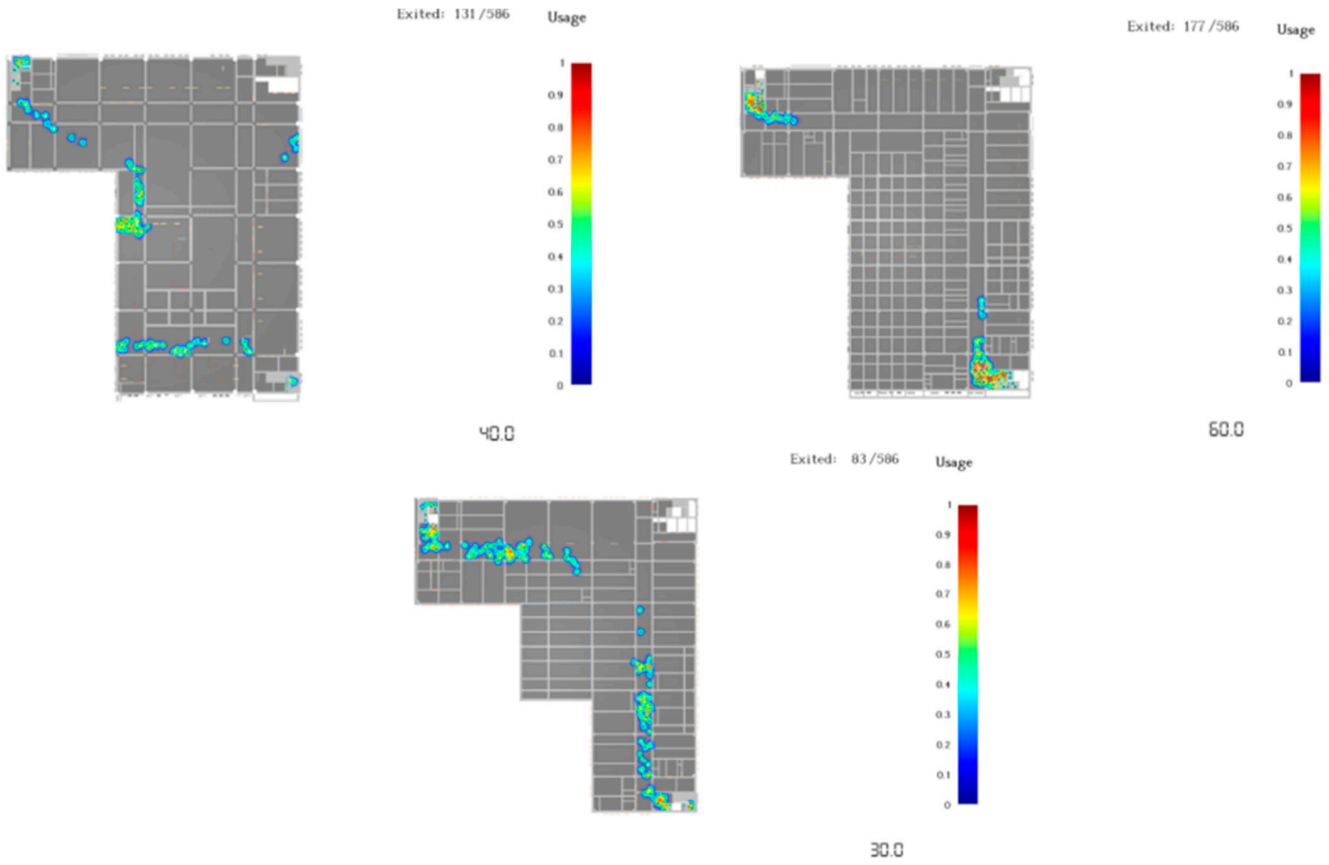


Figure 6. Evacuation Status at Different Times in Hospital A.

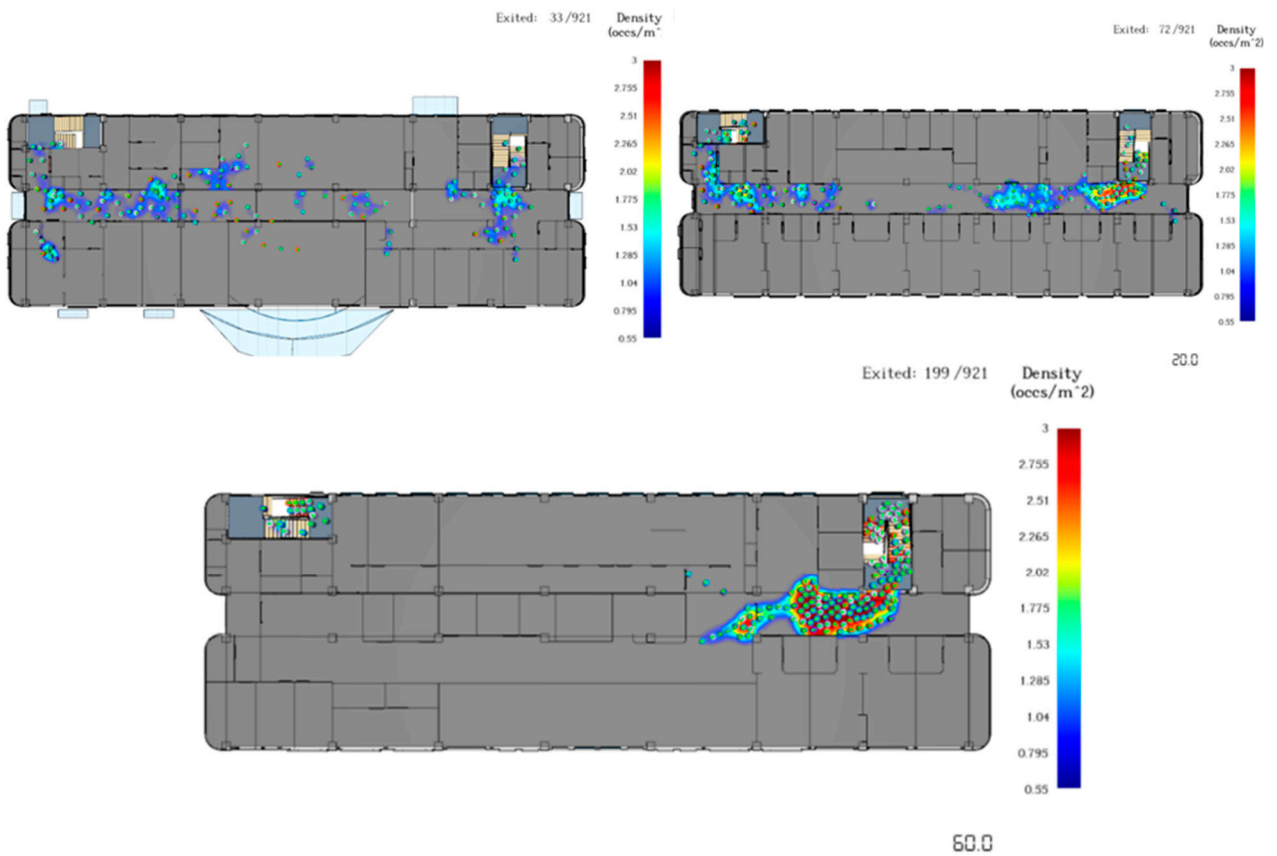


Figure 7. Evacuation Status at Different Times in Hospital D.

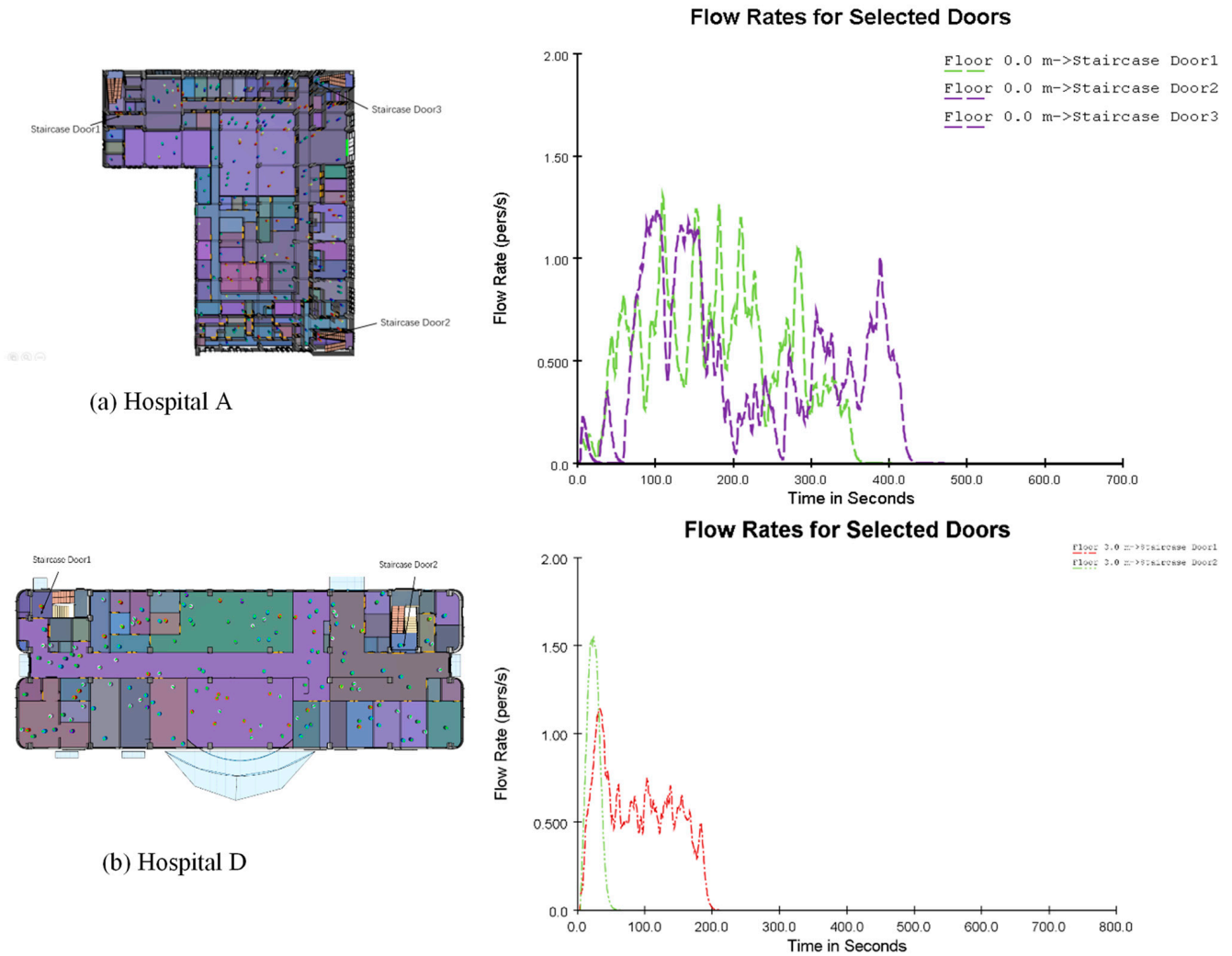


Figure 8. Flow Rates of Stairwell Passage Doors. (a) Hospital A. (b) Hospital D.

Table 7. Key Evacuation Simulation Results Comparison.

Evaluation Indicator	A Hospital	D Hospital	Difference Analysis
Total Evacuation Time (s)	598.3	690.0	A Hospital demonstrates higher efficiency
Last Person Evacuation Time (s)	625.4	735.2	A Hospital shows better tail-end evacuation performance
Maximum Congestion Density (persons/m ²)	1.78 (main exit)	1.99 (intersection of main corridor and stairs)	D Hospital exhibits more severe congestion
Exit Utilization Balance	High; flow distributed evenly across exits	Very low; main exit overcrowded	A Hospital has a more reasonable exit distribution

4.4. Comprehensive Evaluation and Adjustment Integrating Dynamic Simulation Data

After the initial evaluation based on static indicators, to verify the consistency of static evaluation results with actual evacuation performance and to assess the corrective effect of dynamic simulation data, evacuation time data under a unified disaster scenario were obtained through BIM-Pathfinder simulation for the eight hospitals. Due to space limitations, detailed simulations of the other six hospitals are not described; the simulated evacuation times (E1) are shown in Table 8.

Table 8. Simulated Evacuation Times (E1) for Eight Hospitals.

Indicator	A	B	C	D	E	F	G	H
Evacuation Time (E1)	9 min 58 s	8 min 5 s	9 min 11 s	11 min 30 s	9 min 33 s	13 min 17 s	7 min 9 s	6 min 15 s
Ranking	6	3	4	7	5	8	2	1

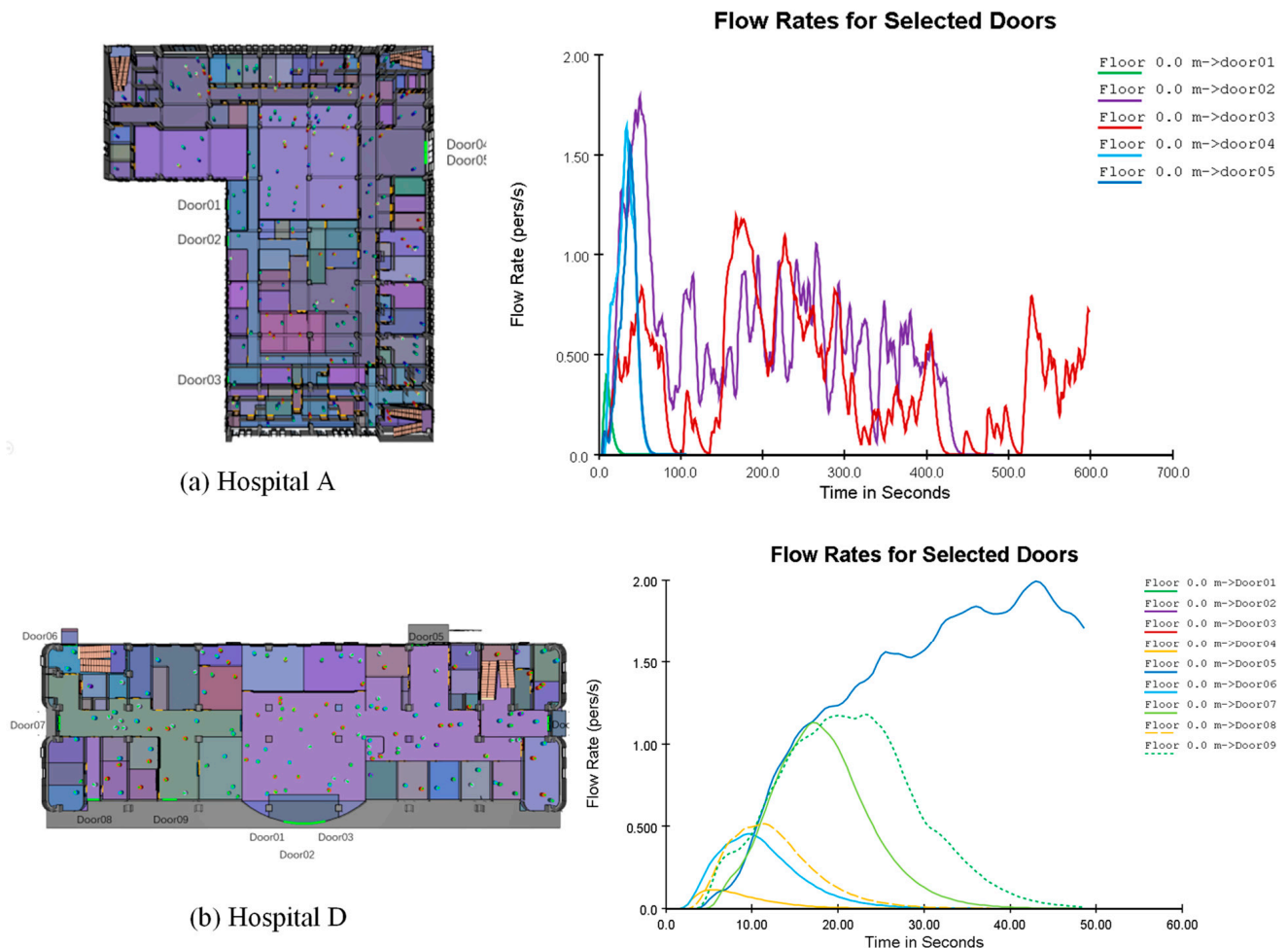


Figure 9. Flow Rates at Main Building Exits. (a) Hospital A. (b) Hospital D.

The simulation rankings broadly validate the TOPSIS assessment results and were subsequently incorporated into the evaluation indicator system to perform further adjustments. By integrating the simulated evacuation times as the E1 indicator into the original 31-indicator evaluation system, a comprehensive dataset of 32 indicators was formed. Reapplying the entropy weight–TOPSIS method produced the revised evaluation results presented in Table 9.

In-depth analysis of ranking changes reveals that, although Hospital G does not excel in certain static hardware indicators, its efficient spatial layout and management measures translated into superior evacuation efficiency (7 min) in the dynamic simulation, reflecting the advantage of “soft” management capabilities. This highlights the significant role of “soft” management capabilities in improving evacuation performance. In contrast, Hospital B, despite favorable static scores, could not fully realize its theoretical performance (8 min) due to hidden flaws in spatial layout. This comparison highlights the limitation of static evaluation systems, which primarily reflect the building’s “innate conditions,” whereas dynamic evacuation simulation can assess their “operational effectiveness” under actual disaster scenarios.

Table 9. Comprehensive Evaluation Results of Safety Evacuation Plans for Eight Outpatient Buildings with Simulated Evacuation Times.

Building	Euclidean Distances		Relative Closeness	Ranking
	Euclidean Distance to Positive Ideal Solution	Euclidean Distance to Negative Ideal Solution		
A	0.12551	0.077	0.37961	6
B	0.07478	0.131	0.63681	3
C	0.09766	0.101	0.50818	5
D	0.15133	0.064	0.29679	7
E	0.08558	0.114	0.57163	4
F	0.18445	0.066	0.26439	8
G	0.07784	0.149	0.65723	2
H	0.06629	0.185	0.73569	1

Moreover, incorporating dynamic data enhances the engineering guidance value of the evaluation. The revised results consider not only static safety conditions but also their practical performance during emergencies. For example, the improvement in Hospital E's ranking demonstrates that its operational management measures played a crucial role in real evacuation scenarios, providing specific directions for optimizing evacuation management strategies.

The integrated static–dynamic evaluation method established in this study, by feeding BIM simulation data back into the assessment system, achieves a transition from “static condition evaluation” to “dynamic performance verification.” This approach not only improves the scientific rigor and accuracy of the evaluation but also identifies buildings with good static conditions but insufficient dynamic performance, providing precise evidence for targeted improvements. It has significant practical implications for enhancing the safety evacuation management of personnel-intensive buildings. By incorporating evacuation simulation data, this methodology allows for more accurate and actionable recommendations for improving evacuation strategies and building design.

5. Discussion

The core contribution of this study lies in establishing a closed-loop framework that integrates entropy weight TOPSIS evaluation with BIM–Pathfinder-based evacuation simulation to verify and calibrate TOPSIS assessment outcomes. Rather than proposing a new simulation theory or algorithm, this research emphasizes methodological integration. The proposed approach enables bidirectional feedback between static multi-criteria decision-making and dynamic performance evaluation, thereby providing a systematic mechanism for enhancing the reliability, interpretability, and practical usability of safety assessment in high-occupancy buildings.

Static design indicators derived from building codes and technical standards constitute the fundamental baseline for life-safety performance, ensuring regulatory compliance and minimum protective measures for occupants. Meanwhile, performance-based safety assessment has become an essential tool for complex or special-function facilities, enabling higher-fidelity evaluations under specific hazard scenarios such as fire or structural emergencies. The framework developed in this study is not intended to replace code-based design requirements or established performance-based methods. Instead, it serves as a supplementary mechanism that bridges static multi-criteria evaluation and dynamic evacuation simulation, thereby enabling refined risk identification and decision support in buildings that already meet regulatory design requirements. This static–dynamic coupling provides a more evidence-driven pathway for optimizing emergency preparedness and evacuation management in real-world practice.

Although this study adopts the entropy weight TOPSIS method, several other multi-criteria decision-making (MCDM) techniques—such as AHP, PROMETHEE, and ELECTRE—have also been widely applied in safety evaluation and emergency decision support. Compared with expert-judgment-based AHP, entropy weight TOPSIS reduces subjectivity by computing indicator weights directly from data distribution characteristics, while methods such as PROMETHEE offer complementary advantages in preference visualization and outranking analysis. In this work, entropy weight TOPSIS was selected to support the proposed closed-loop evaluation–simulation–feedback system based on its reproducibility and suitability for quantitative indicator structures. Future studies will conduct comparative analyses of multiple MCDM methods and perform additional external validation to further enhance the robustness and generalizability of the evaluation framework.

Finally, the dynamic simulation conducted in this study demonstrates that certain hospitals with strong static performance indicators may still experience bottlenecks during emergency evacuation, and vice versa. This highlights the critical need for integrating digital simulation feedback into static safety assessment processes. In future work, the current framework can be extended to incorporate other simulation platforms (e.g., FDS-based smoke spread models) and multi-hazard scenarios, thereby offering a broader decision-support capability for emergency management and building safety planning.

6. Conclusions

This study addresses the disconnection between static indicators and dynamic performance in the safety evacuation assessment of personnel-intensive buildings by constructing an integrated analytical framework that combines the entropy weight–TOPSIS method with BIM-Pathfinder simulation. By integrating precise spatial data from building information models, microscopic simulation of dynamic evacuation processes, and multi-criteria decision-making methods, the framework enables a full-process analysis from static evaluation to dynamic validation. The empirical results demonstrate that the framework not only systematically quantifies the static conditions of a building in terms of spatial organization, facility configuration, and management level, but, more importantly, by incorporating dynamic simulation, reveals the actual operational effectiveness of these static conditions under disaster disturbances. This overcomes the limitations of traditional static assessment methods, which often fail to capture the true evacuation process.

The theoretical contributions of this study are highlighted in three aspects. First, by establishing the intrinsic link between static and dynamic indicators, it confirms the significant corrective effect of dynamic simulation data on static evaluation results, thereby underscoring the limitations of relying solely on static indicators for safety assessment. Second, through the mapping analysis between dynamic simulation outcomes and static evaluation indicators, the study effectively elucidates the nonlinear mechanisms and coupling effects of various indicators during the evacuation process. This overcomes the constraints of traditional assessments that assume linear additive weighting, providing a new paradigm for constructing more explanatory evacuation safety assessment theories. Third, by deeply integrating building information models with evacuation simulation, the study advances the application of digital technologies in emergency management from mere visualization to analytical decision support, offering substantial contributions to the innovation of building safety evaluation methods.

Despite the achieved progress, several aspects require further improvement. On one hand, human behavior under disaster conditions exhibits high uncertainty. In the current simulation, the modeling of personnel behavior is still based on simplified assumptions. Future work could incorporate behavioral observation data to refine movement parameters

and decision-making rules for different categories of personnel, thereby enhancing the realism of behavior simulation. On the other hand, this study primarily focuses on a single disaster scenario—earthquake. Future simulations could incorporate multiple coupled hazards, such as fire and localized structural collapse, to improve the applicability of the model in complex disaster scenarios. Such enhancements would further strengthen the alignment between dynamic simulation and the evaluation indicator system, thereby increasing the scientific rigor and practical utility of the assessment results.

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Abbreviations

The following abbreviations are used in this manuscript:

MCDM	Multi-Criteria Decision-Making
AHP	Analytic Hierarchy Process
DEA	Data Envelopment Analysis
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
BIM	Building Information Modeling
IFC	Industry Foundation Classes
FDS	Fire Dynamics Simulator

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