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Article

Exploring Family Ties and Interpersonal Dynamics—A Geospatial Simulation Analyzing Their Influence on Evacuation Efficiency within Urban Communities

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Abstract: Guaranteeing efficient evacuations in urban communities is critical for preserving lives, minimizing disaster impacts, and promoting community resilience. Challenges such as high population density, limited evacuation routes, and communication breakdowns complicate evacuation efforts. Vulnerable populations, urban infrastructure constraints, and the increasing frequency of disasters further contribute to the complexity. Despite these challenges, the importance of timely evacuations lies in safeguarding human safety, enabling rapid disaster response, preserving critical infrastructure, and reducing economic losses. Overcoming these hurdles necessitates comprehensive planning, investment in resilient infrastructure, effective communication strategies, and continuous community engagement to foster preparedness and enhance evacuation efficiency. This research looks into the complexities of evacuation dynamics within urban residential areas, placing a particular focus on the interaction between joint-rental arrangements and family ties and their influence on evacuation strategies during emergency situations. Using agent-based modeling, evacuation simulation scenarios are implemented using the Changhongfang community (Shanghai) while systematically exploring how diverse interpersonal relationships impact the efficiency of evacuation processes. The adopted methodology encompasses a series of group experiments designed to determine the optimal proportions of joint-rental occupants within the community. Furthermore, the research examines the impact of various exit selection strategies on evacuation efficiency. Simulation outcomes shed light on the fundamental role of interpersonal factors in shaping the outcomes of emergency evacuations. Additionally, this study emphasizes the critical importance of strategic exit selections, revealing their potential to significantly enhance overall evacuation efficiency in urban settings.

Keywords: emergency evacuation; interpersonal relationships; residential community; multi exits; agent-based modeling; joint-rental; family-tie; GIS

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1. Introduction

Within the complex fabric of urban communities, emergency evacuation stands as a crucial shield against looming threats and unforeseen disasters [1]. At the intersection of safety and urgency, urban zones, especially those crowded with human activity and density, demand evacuation blueprints that are not only swift and reliable but also mindful of the complex weave of interpersonal relationships and family ties [2]. These connections, deeply rooted in the human psyche, could significantly alter the patterns and outcomes of emergency responses, making them a critical aspect to consider in developing effective evacuation protocols.

Specifically, in Chinese urban communities, family-tie relationships are among the most common interpersonal relationships in residential areas [3]. With the development of China's urbanization process, a growing number of young people are leaving their hometowns to work or study in developed cities [4]. In terms of live space, "joint rental" refers to an apartment or house that is rented jointly by multiple individuals; these individuals share the responsibilities and costs associated with the apartment, including rent, utilities, and other expenses; such arrangements can be common in urban environments, among students, or in situations where housing is expensive. This type of agreement helps distribute expenses and makes living in certain areas more affordable for individuals. The concept of joint rental has been gaining popularity in China in recent years, particularly in major cities where the cost of living is relatively high [5]. This is driven by the younger generation, increasingly seeking flexible and affordable living arrangements. According to a report by China Daily, the shared housing market in China is estimated to be worth around 50 billion yuan (USD 7.8 billion) in 2021, with a year-on-year growth rate of over 100% [6].

During emergencies, different interpersonal dynamics and relationships can lead to completely dissimilar emergency evacuation strategies and, therefore, drive different evacuation behaviors within urban settlements [7]. This divergence arises because individuals often prioritize the safety of close family members or heed the decisions of dominant figures in their peer groups rather than strictly following standard evacuation procedures. For instance, in multicultural urban areas, linguistic or cultural barriers can result in residents awaiting familiar cues or community translations, causing varied evacuation responses [8].

Consequently, it is essential to explore the impact of different interpersonal relationships on evacuation efficiency. In existing relevant research, interpersonal relationships such as leader-and-follower [9], people with and without evacuation experience [10], colleagues or friends [11], and staff and passages [12] were widely mentioned; evacuation scenarios involved were mostly in various public settings like office buildings [11,13,14], subway systems [15–17], parks [18–20], and educational institutions [21–23], among others. Yet, the sphere of family ties in evacuation processes remains relatively underexplored. While Toledo et al. [24] analyzed family decision-making dynamics during fires, and Rodriguez and Liu, Delin et al. [25] studied familial behaviors in flood evacuations, comprehensive studies dedicated solely to understanding the unique intricacies of family ties in evacuations are sparse, presenting a gap our research intends to bridge.

Exit selection is often thought to be influenced by the interplay of factors such as evacuee interaction [26], spatial distance, and occupant density [27]. Additionally, human psychology, door placement, width, obstacle positioning, environmental lighting, and crowd distribution play crucial roles in this regard [28].

Evacuation planning and management have been extensively studied. Nevertheless, the current scientific literature lacks further studies that consider evacuation behaviors under interpersonal relationships in residential areas, especially evacuation behavior under joint-rental relationships, which has rarely been studied. Likewise, in the context of current exit selection schemes used to simulate evacuation dynamics, it is assumed that all evacuees possess knowledge regarding the locations of all available exits. However, in a practical scenario, this assumption does not align with reality. Therefore, the motivation of this study is to propose and implement a simulation of evacuation enriched with evacuation behaviors determined by interpersonal relationships in residential areas, as well as simultaneously explore the impact of different exit selection principles on evacuation efficiency. To fulfill this objective, we developed an agent-based model; we meticulously studied the unique challenges presented by joint-rental dynamics and then assessed the effectiveness of various exit selection strategies within these constraints. Our research innovatively blends qualitative and quantitative methodologies, ensuring a holistic approach to understanding evacuation behaviors. The pivotal contributions of our study are threefold: first, we delve into the understudied domain of joint-rental evacuation behaviors; second, we challenge the conventional wisdom around exit selection by juxtaposing it against real-world contexts;

and third, we offer practical insights that can reshape evacuation planning in residential areas, making them more adaptive and efficient.

In the subsequent sections, we outline the methodology underpinning the evacuation agents, encompassing both their evacuation behaviors and the principles guiding exit selection. We then delve into a detailed description of the study area, illustrating the community layout and elucidating the parameters set for the evacuees. This is followed by a rigorous combined qualitative and quantitative analysis of our findings. This manuscript culminates in drawing conclusions, underscoring the broader implications of our research.

2. Methodology

Agent-based modeling (ABM) stands out as a powerful tool that enables researchers to dissect intricate interactions and emergent behaviors among individual entities or "agents" in a given environment. The selection of ABM for this study was underpinned by its capability to provide granular insights into individual behaviors while also allowing for the examination of their collective outcomes, particularly in dynamic scenarios like evacuations. At its core, ABM typically comprises individual agents and their operating environment, which, in our context, are represented by 3D models of evacuees and the corresponding evacuation space. This study further refines the model by incorporating specific evacuation behaviors, namely, family-tie evacuations and joint-rental evacuations, which encapsulate the nuanced interpersonal dynamics often overlooked in traditional evacuation studies. Additionally, the model factors in exit selection principles dictate the strategies agents employ to navigate their way to safety. As we delve deeper into the methodology, it is essential to view ABM not merely as a modeling tool but as a bridge that connects individual actions to systemic outcomes, providing a holistic lens to understand and potentially improve evacuation processes. Figure 1 shows the methodological framework of this study.

As shown in Figure 1, this study consists of three main parts:

1. Data Acquisition: Obtain spatial data of the residential area to construct a three-dimensional evacuation space model. Collect resident data to accurately replicate the evacuation process, making the simulation results more realistic and credible;
2. Evacuation Simulation: Conduct multiple evacuation simulation experiments under different scenarios by setting various proportions of family relationships and cohabitation ratios in residential buildings, combined with different exit choice probabilities;
3. Emergency Management Analysis: Based on the analysis of the evacuation simulation results, determine the maximum recommended joint-rental ratio for different types of residential buildings and the optimal exit choice strategy during residential area evacuation. Additionally, propose corresponding optimization suggestions for the indoor and outdoor evacuation process in residential areas based on the above simulation results.

Compared to previous studies, the main innovations of this research are as follows:

By considering the different evacuation behaviors of joint-rental and family members, this study determines the maximum recommended joint-rental ratio for different types of residential buildings.

By simulating multiple exit choice scenarios, the evacuation simulation results better reflect the complexity of actual resident evacuations, thereby enhancing the practicality and accuracy of this model.

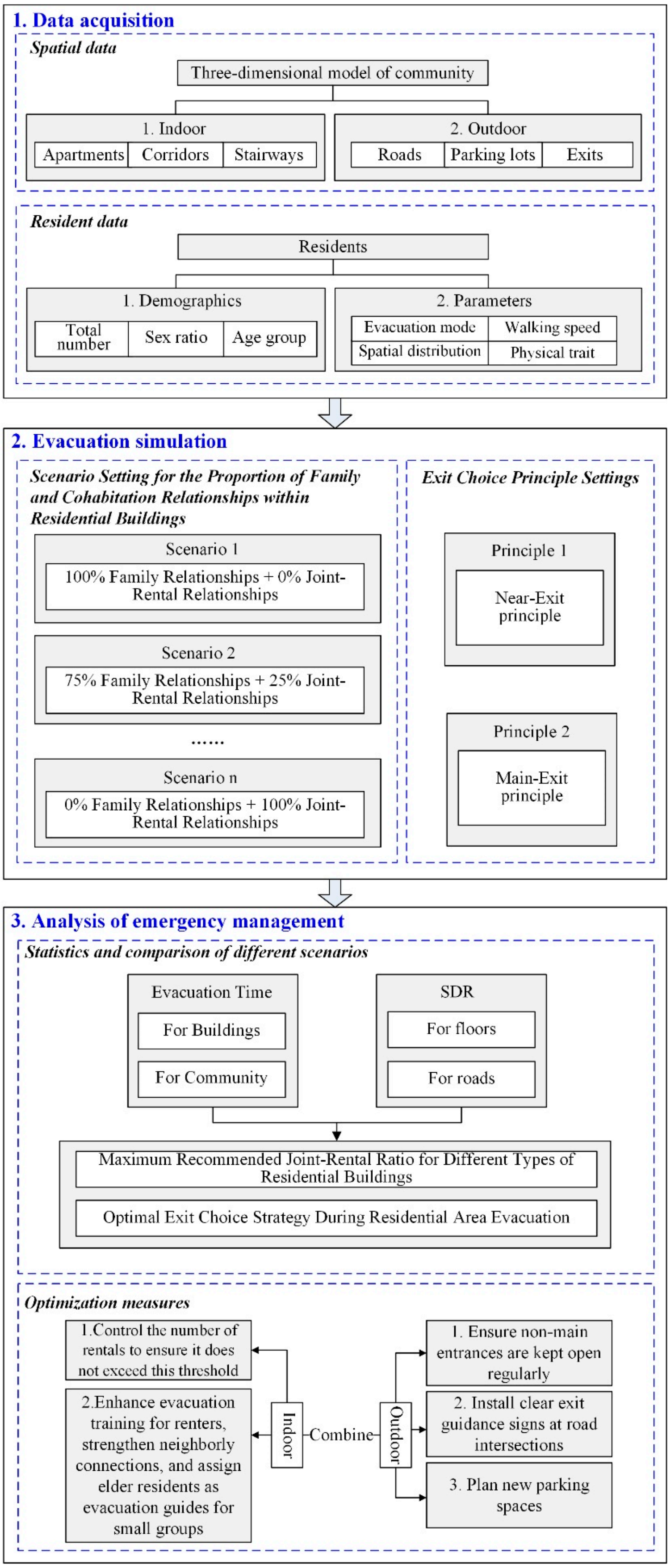


Figure 1. Methodological Framework.

2.1. Evacuation Agents for Family-Tie Relationships and Joint-Rental Relationships

A family represents a collective entity that is bound together through the institution of marriage, biological kinship, or legal adoption [29]. Within this collective structure, family members exhibit mutual trust, a profound level of interdependence, and a strong sense of responsibility and cohesion. Due to these intricate bonds, during emergent situations, residents are often reluctant to evacuate independently, preferring to wait until all members of their familial unit have gathered, thereby ensuring their collective safety before departing their residence. This behavioral pattern is termed "family teamwork mode" [30], representing a distinct evacuation approach based on familial relationships, as illustrated in Figure 2.

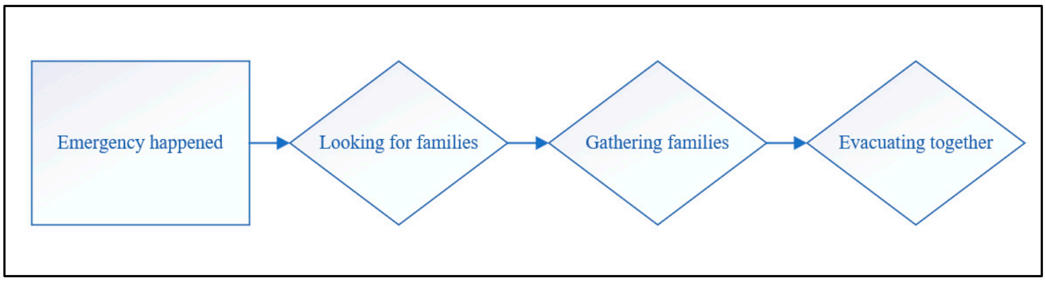


Figure 2. Evacuation strategy for family-tie relationships.

Figure 3 shows the framework for designing evacuation agents for family-tie relationships; $T_{respond}$ represents the delay time before residents look for their families, then residents need to move to the gathering point to wait for all family members to gather; $T_{disscuss}$ represents the time families need to realize the current emergency situation before evacuating. Finally, in order to reach the final exit, they need to select the same exit and adjust to the same speed. In this study, this special evacuation mode is "Family Evacuation Behavior", as illustrated in Figure 6.

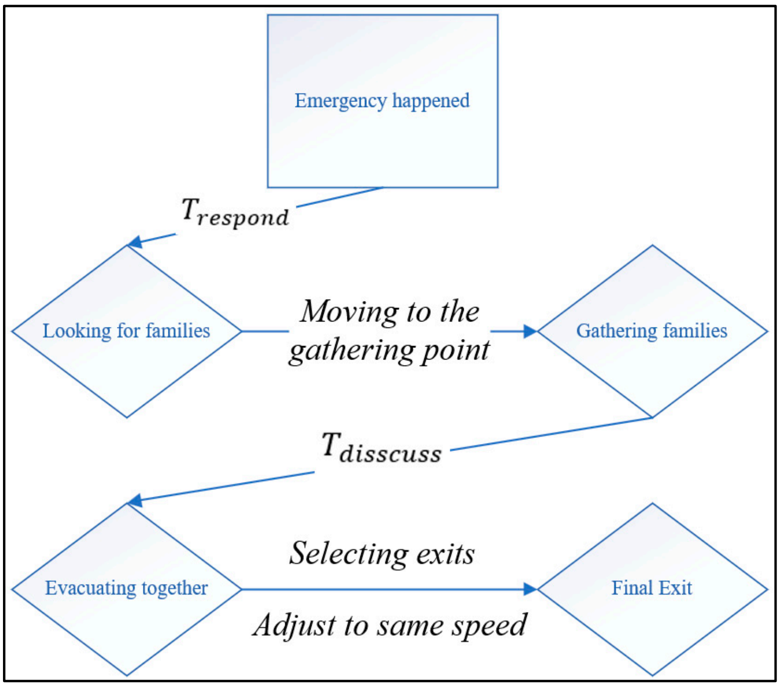


Figure 3. Framework of evacuation agent for family-tie relationships.

Joint-rental relationships refer to a situation where two or more people rent a property together and share the responsibility for paying the rent and maintaining the property. In a joint-rental relationship, it is difficult to find reliable and trustworthy housemates, as many people are still reluctant to live with strangers. Therefore, in the event of an emergency, most people in a joint-rental relationship will choose to evacuate alone, and the evacuation strategy process is shown in Figure 4.

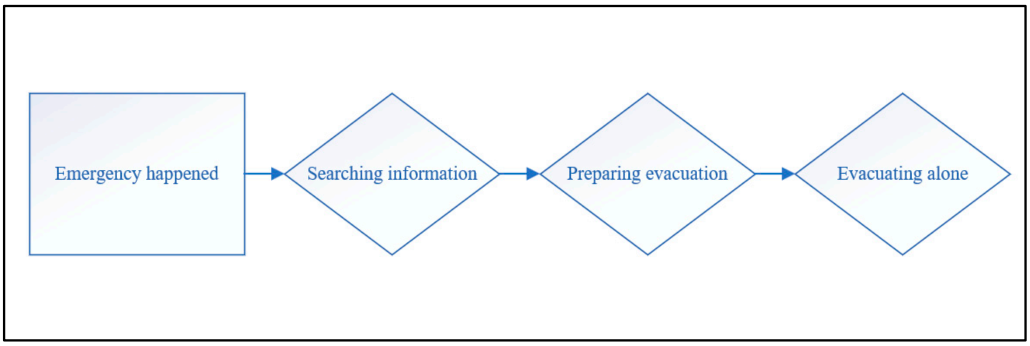


Figure 4. Evacuation strategy for joint-rental relationships.

Figure 5 shows the framework of the proposed evacuation agent-based model to simulate joint-rental relationships. For these, three evacuation behaviors are implemented: (1) Instant behavior: residents start evacuating without hesitation after an emergency happens; (2) Delay behavior: residents stay in their original position for a while (T_{Delay}) to realize the current situation, then start evacuating; (3) Detained behavior: residents firstly go to a second place for a specific purpose, such as packing up valuable items, stay there for a while (T_{Stay}), and then start evacuating. These three behaviors are illustrated in Figure 6. After residents have selected their evacuation behavior, they also need to decide which exit can be chosen to evacuate. Finally, they will leave in the direction of the final exit.

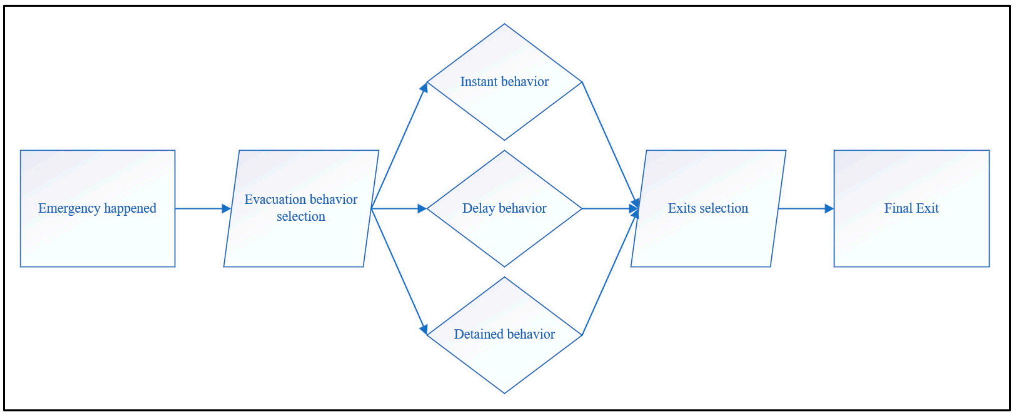


Figure 5. Framework of evacuation agent for joint-rental relationships.

The selection probabilities of the three above-mentioned behaviors ($P_{Instant}$, P_{Delay}, $P_{Detained}$) satisfy the following equation:

$$P_{Instant} + P_{Delay} + P_{Detained} = 100\% \quad (1)$$

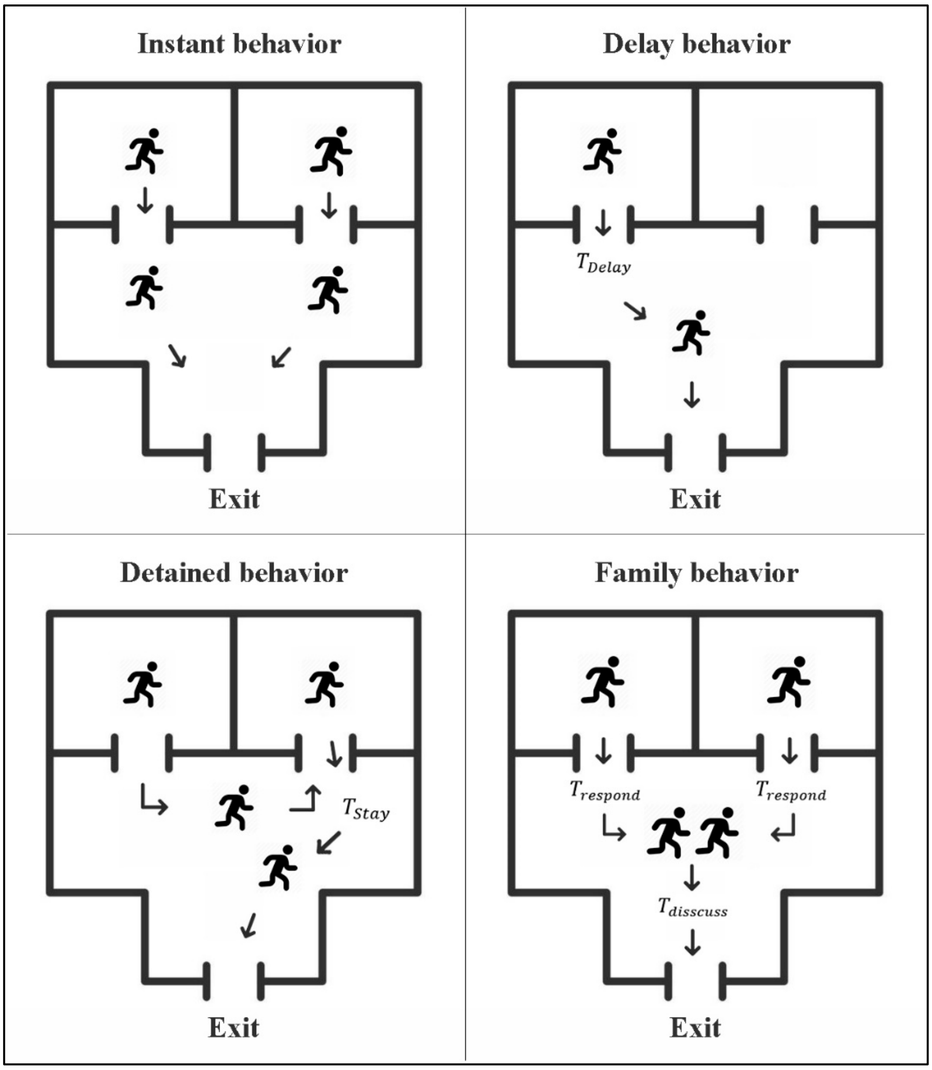


Figure 6. Illustration for each evacuation behavior.

2.2. ABM and BIM in Unity

The agents for the two relationships (family-tie and join-rental) in this study were constructed using Unity. Unity offers a notable advantage through its navigation function, which utilizes the A* search algorithm alongside a triangulated navigation mesh to generate paths, as illustrated in Figure 7 [31]. The A* search algorithm employed within the Unity framework in this study functions as a pathfinding and graph traversal method, systematically calculating the most efficient path between two points by evaluating the cost of each potential path, balancing the actual distance traveled with the estimated distance to the destination, thereby ensuring optimality in real-time navigation scenarios.

Such paths consist of a sequence of points situated along the edges of the mesh triangles.

The diagram in Figure 6 illustrates the projected path of an evacuee within a 2D room layout. The evacuee is initially positioned at the upper left side of the room and intends to exit from the bottom. The thin blue lines in the figure indicate the navigation mesh, while the walls obstruct the direct path to the exit. The evacuee's path is marked with a thick green line, and the red circles indicate the waypoints. Each edge that intersects the path generates a waypoint.

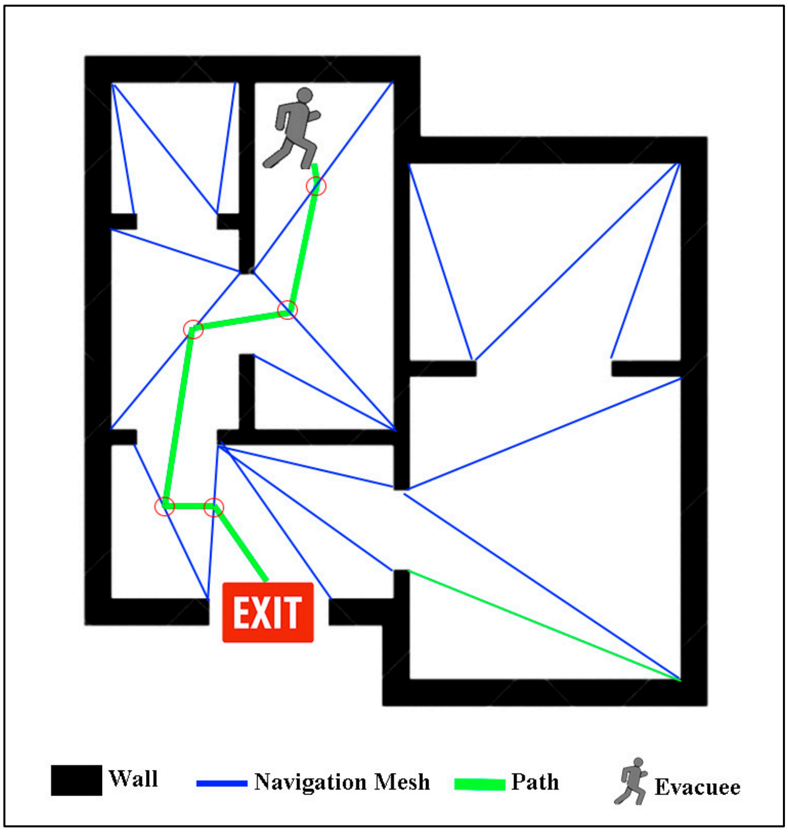


Figure 7. Illustrates the process of path generation using the A* search algorithm.

This study's Agent-Based Model (ABM) adheres to the ODD (Overview, Design concepts, and Details) protocol [32] to ensure clear and effective description and communication. The ODD protocol offers a structured framework that improves the model's transparency, comprehensibility, and transparency. In the validation and verification section of the ABM, historical evacuation data from the Changhongfang residential area [3] were used for debugging, code review, and calibration.

In Unity, the functionality of the agent model is realized through components. The components and their functions used in this study are shown in Table 1.

Table 1. Introduction to ABM Components.

Component Type		Component Name	Component Function
Non-customized components	Unity built-in components	Transform	Controlling the position, rotation, and scale of objects
		Mesh Filter	Controlling the shape displayed by objects
		Mesh Renderer	Controlling the rendering of objects
		Rigidbody	Controlling the weight of objects
		NavMeshAgent	Controlling the movement speed of objects
Customized components	Shared components	Attribute	Setting the interpersonal relationships of agents
		Exits Choice	Setting the exit choice probability of agents
		Behavior Choice	Setting the behavior choice probability of agents
		Output Data	Setting the content of agent output information
	Exclusives to joint-rental relationships	Instant Evacuation	Immediate evacuation behavior mode of agents
		Delay Evacuation	Delayed evacuation behavior mode of agents
		Detained Evacuation	Return evacuation behavior mode of agents
	Exclusive to family relationships	Gather Evacuation	Group evacuation behavior mode of agents

This study uses five built-in non-customized components of Unity and eight customized components (including four shared components, three exclusives to joint-rental relationships, and one exclusive to family relationships) to simulate the evacuation strategies under joint-rental and family relationships.

Building Information Modeling (BIM) is an advanced multidimensional modeling process that integrates detailed architectural, engineering, and construction information into a unified digital representation. To implement the BIM portion, Probuilder was employed. Probuilder is an integrated tool within Unity that facilitates the creation of 3D models, such as stairs, planes, walls, and corridors, with ease [31]. Furthermore, models constructed using ProBuilder can seamlessly integrate with the navigation mesh, as shown in Figure 8.

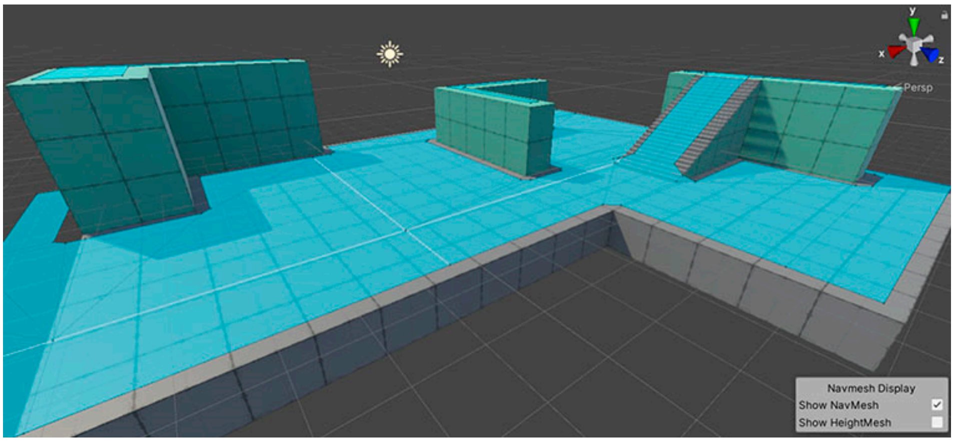


Figure 8. Showcases an example of a 3D model created using ProBuilder.

Moreover, Unity possesses the capability to simulate a realistic "movement effect" for evacuees. Within the simulation, the speed of the simulated evacuees incrementally accelerates from zero and gradually decelerates to zero as they approach the exit instead of an abrupt change in speed. Additionally, Unity incorporates realistic collision effects, preventing evacuees from simply passing through each other.

2.3. Suggested Max Ratio of Joint-Rental

From the occurrence of an emergency to the evacuation of personnel, this period of time ($T_{DelayBE}$) is consisted of the following parts:

$$T_{DelayBE} = T_{notification} + T_{reaction} + T_{preparation} \quad (2)$$

where $T_{notification}$ represents the time of fire detection (notification time); $T_{reaction}$ denotes the duration from hearing the alarm or observing signs of fire to deciding on action (reaction time), and $T_{preparation}$ signifies the preparation time before evacuees commence evacuation (preparation time) [31].

Generally speaking, due to living alone, the delay time before evacuation for joint rental is much longer than that for family members. Therefore, the suggested max ratio can be calculated by adjusting the proportion of family members and joint-rental tenants inside different layout buildings.

2.4. Exit Selection Principle

In a multi-exit evacuation scenario, there are generally two kinds of exit selection strategies that people pursue: (1) selecting the exit closest to themselves; (2) selecting the exit they are most familiar with (generally the main exit). Based on the aforementioned two strategies, this study proposes two principles for exit selection:

Near-Exit principle: People choose the nearest exit for evacuation based on their location and the Euclidian distance to each exit;

Main-Exit principle: If the number of exits is N_{Exits}, people have different selection probabilities for different exits; among them, the probability of selecting the main exit P_{ME} satisfies the following equation:

$$100\% > P_{ME} > \frac{1}{N_{Exits}} \times 100\% \quad (3)$$

2.5. Speed Decrease Ratio

Speed Decrease Ratio (SDR) [33] was used to reveal the crowded degree of evacuees during the evacuation process:

$$SDR = \frac{(V_{max} - V_T)}{V_{max}} \times 100\% \quad (4)$$

where V_{max} denotes the maximum speed of the evacuee throughout the entire evacuation process, and V_T represents the real-time speed of an evacuee. It is deemed crowded if the SDR surpasses a certain threshold.

3. Study Area and Evacuees

3.1. Study Area

To showcase the effectiveness of this framework, a case study was conducted in Changhongfang, a residential community located in Xuhui District, Shanghai, China. In 2017, an unmanned aerial vehicle captured an aerial photograph of Changhongfang with a resolution of 30 cm, depicted in Figure 9.

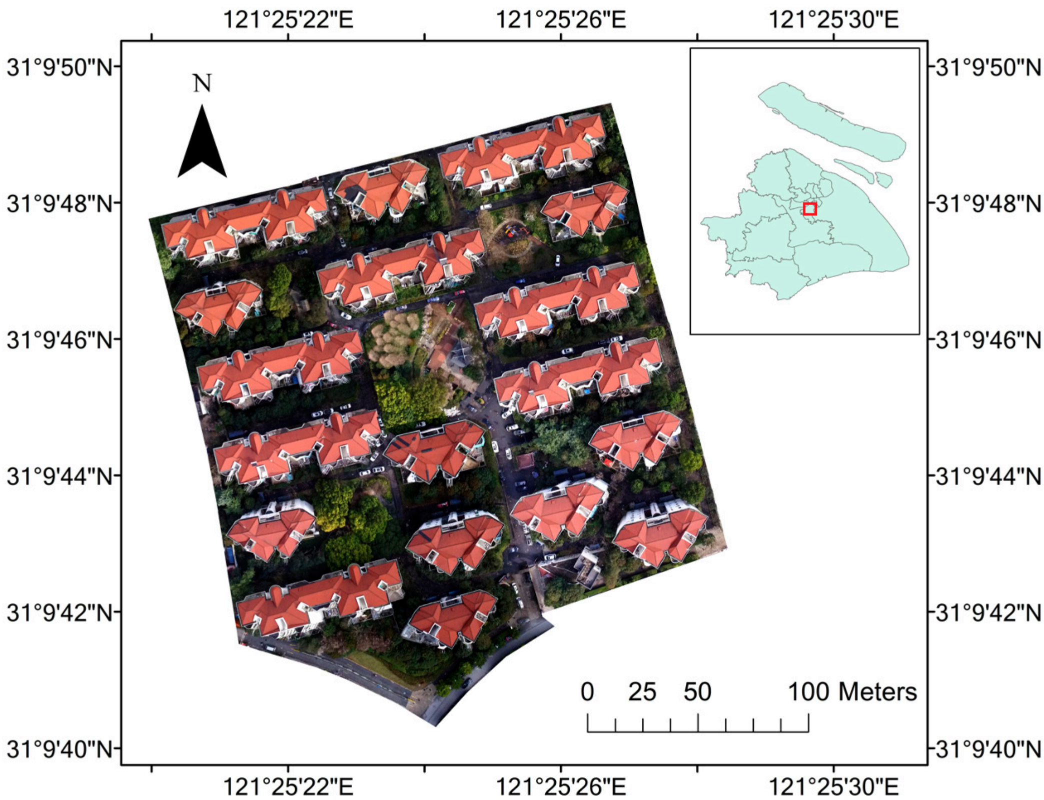


Figure 9. Illustrates an aerial photograph of Changhongfang Community, located in Xuhui District, Shanghai, China.

The Changhongfang residential area, located in the Xuhui District of Shanghai, is surrounded by extensive commercial and school districts. This leads to a prevalent cohabitation situation due to the large number of migrant workers and student groups. These unique characteristics significantly influence the interpersonal relationships within the community, particularly family ties and joint-rental ties.

It comprises 18 residential buildings, consisting of four four-story buildings, three five-story buildings, and eleven six-story buildings. The community features two exits, situated in the south and north, with the south exit serving as the primary exit. Thanks to its urban diversity, the Changhongfang community was chosen as the study area to implement the present study.

3.2. Community's Spatial Arrangement Information

The community's layout data are divided into outdoor and indoor categories. Indoor data include rooms, corridors, and stairways within the buildings, collected through architectural drawings and field surveys, as depicted in Figure 10. Figure 11 presents an illustration of the detailed interior structure of a four-story building.

In contrast, outdoor data encompass exits, roads, and parking lots acquired through field measurements utilizing an unmanned aerial vehicle. Through the integration of indoor and outdoor data, a comprehensive 3D model of the community was developed, as depicted in Figure 12.

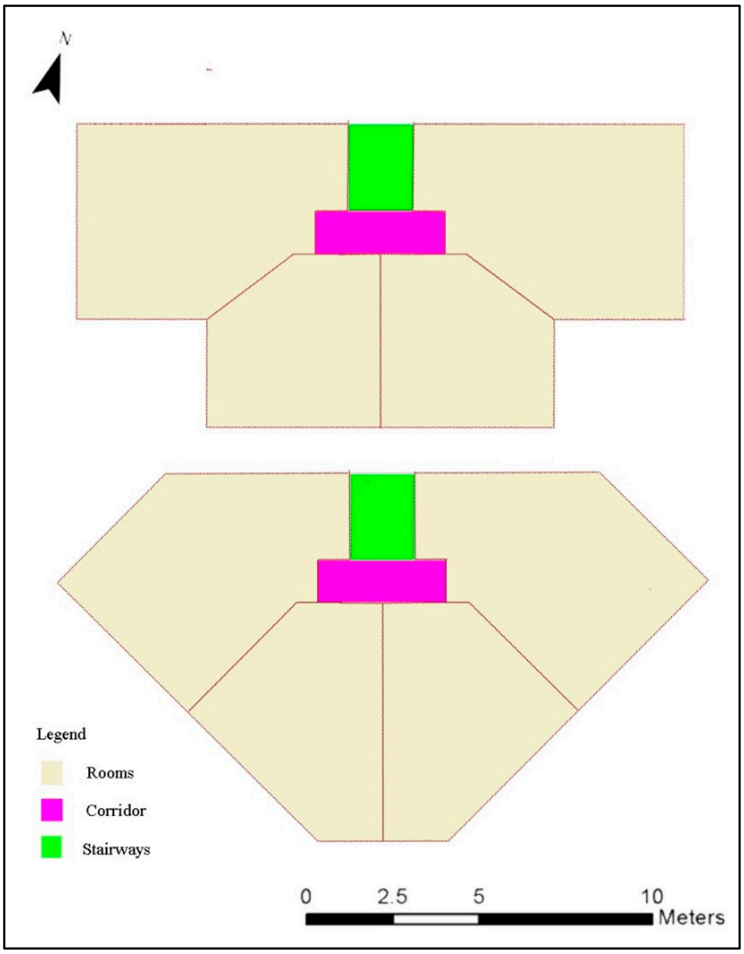


Figure 10. Displays the layout of indoor stairways, rooms, and corridors within community.

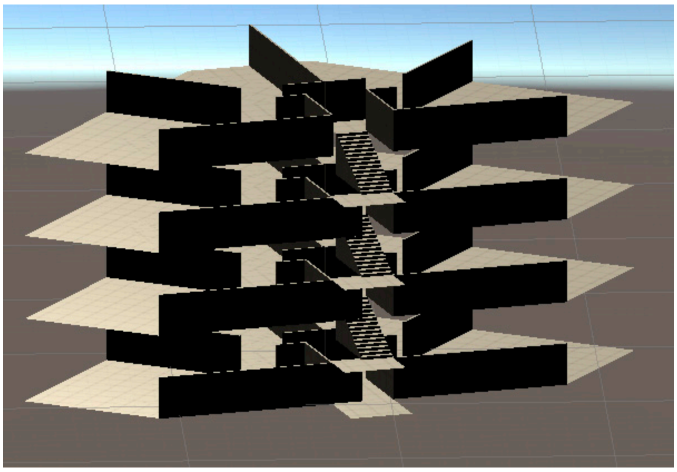


Figure 11. Showcases a 3D model of a 4-story building within community.

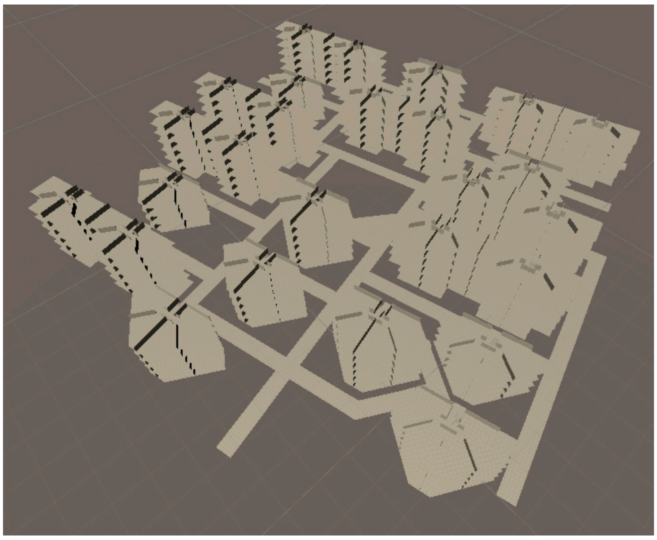


Figure 12. Presents a 3D model of community.

3.3. Evacuees

The evacuees' data in this case study refer to residents of the Changhongfang Community:

(1) Demographic data reveal that according to the sixth Population Census of China, Changhongfang Community housed 1490 residents. Among them, there were 703 males and 787 females, comprising 1362 permanent residents with family ties and 128 external residents in joint-rental relationships. Figure 13 shows the spatial distribution of the number of residents within the 18 residential buildings in the community;

(2) Walking speed varies across different age and sex groups during the entire evacuation process. Table 2 presents the average walking speed of various sex and age categories. The speed data were derived from pedestrian speed measurements conducted in Shanghai in 2003 [34].

The mean velocities for children aged 10 and below, as derived from prior research findings [35], are depicted in Figure 14.

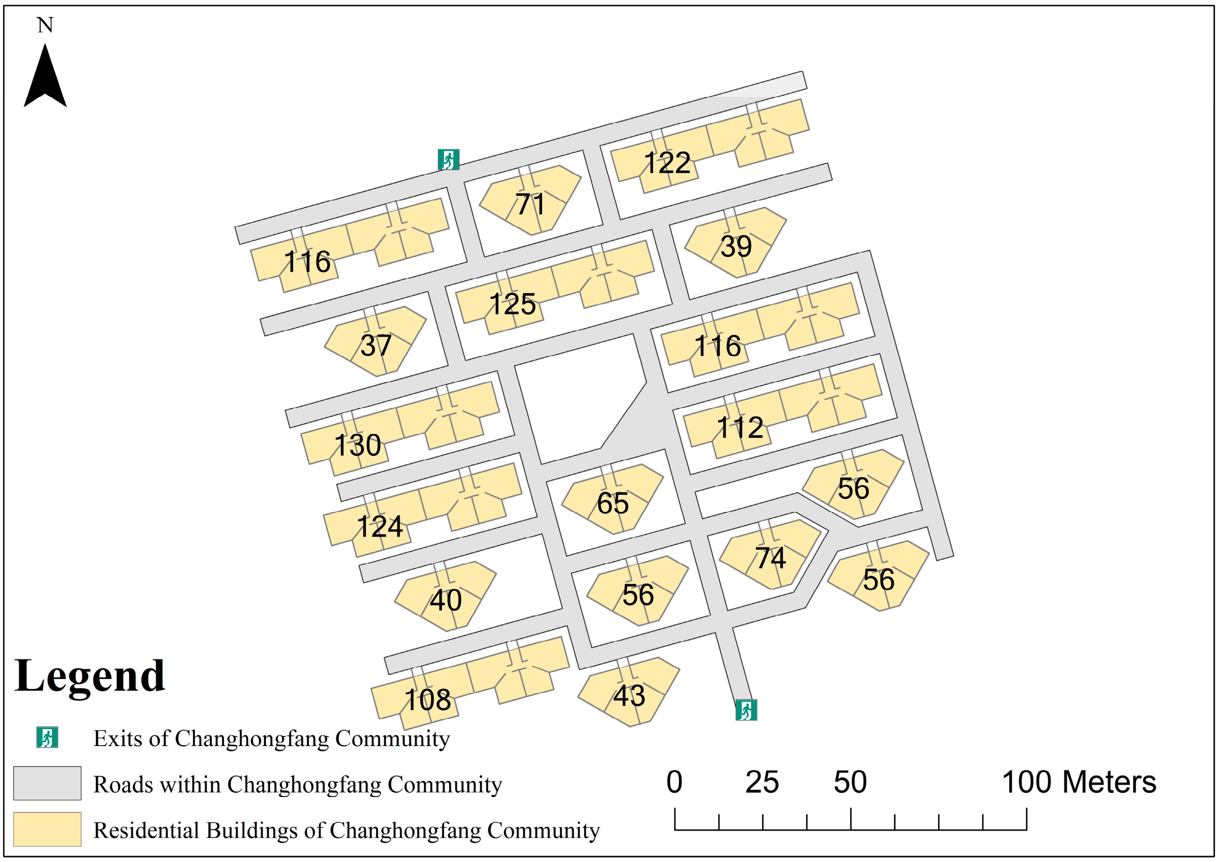


Figure 13. The spatial distribution of the number of residents in each residential building in the Changhongfang community.

Table 2. Walking speeds of different age and sex groups. Taken from [34].

Age Group	Average Speed (m/s)	Samples' Number
Young male	1.32	949
Young female	1.27	1002
Middle-aged male	1.25	829
Middle-aged female	1.20	621
Elderly male	1.10	286
Elderly female	1.08	246

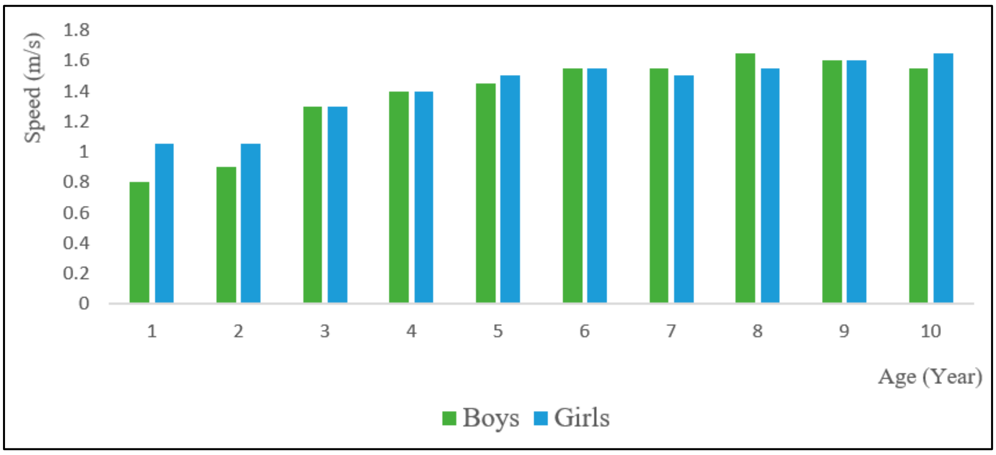


Figure 14. A bar graph illustrating the mean walking velocities of children across various age groups.

Prior research indicates that pedestrian speeds adhere to a Gaussian (normal) distribution, characterized by a deviation factor of 0 and a kurtosis factor of 3 [33]. In alignment with these findings, the walking velocities of residents in this study, segregated by gender and age, also follow a Gaussian distribution. For instance, Figure 15 illustrates the Gaussian distribution of walking speeds specifically for young females;

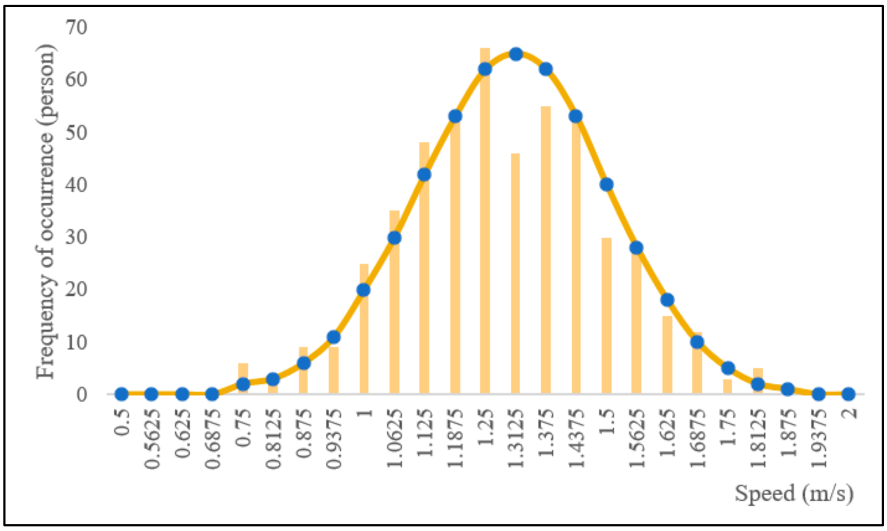


Figure 15. Displays the Gaussian distribution of walking speeds for young females.

(3) Spatial Distribution of Residents: Within the study area, residents are situated across various residential structures. Demographic details such as total population, age demographics, and gender ratios can be sourced from census data. However, specific family compositions remain absent from such data. Consequently, we approximated the residents' spatial distribution by considering each building's apartment occupancy capacity and supplemented this with insights from field surveys;

(4) Physical trait: Within the Unity framework, a cylinder symbolizes the spatial area occupied by a resident. The diameter of this cylinder is determined by the resident's shoulder width, an essential factor for collision detection and path planning throughout the simulation. Drawing from prior studies on Chinese physical dimensions, we established shoulder widths pertinent to various age groups, as detailed in Table 3 [36].

Table 3. Widths of shoulders for different age groups. Taken from [36].

Age Group	Width of Shoulder (cm)
Elderly male	40.5
Elderly female	39.0
Middle-aged male	41.9
Middle-aged female	39.5
Young male	41.0
Young female	38.0
Children	35.0

3.4. Parameter Settings

There are three kinds of parameter settings in this study, as shown in Table 4.

Table 4. Parameter settings for evacuation system.

Parameter Types	Parameter Name	Parameter Values	Parameter Explanation
Joint-Rental Exclusives	T_{Delay}	10 s~30 s	Delay time before evacuation in delay behavior mode
	T_{Stay}	10 s~20 s	Stay duration after reaching the second target point in detained behavior mode
	$P_{Instant}$	30%	Probability of choosing immediate evacuation behavior
	P_{Delay}	40%	Probability of choosing delay evacuation behavior
	$P_{Detained}$	30%	Probability of choosing detained evacuation behavior
	$T_{reaction} + T_{preparation}$	60 s~90 s	Range of values for the sum of reaction time and preparation time
Family Exclusives	$T_{respond}$	0 s~20 s	Reaction time before evacuation in group behavior mode
	$T_{disscuss}$	0 s~15 s	Time spent deliberating after people gather
	$T_{reaction} + T_{preparation}$	0s~30 s	Range of values for the sum of reaction time and preparation time
General	$T_{notification}$	4 mins	Duration from the occurrence of the emergency to the issuance of the notification
	P_{ME}	70%	Probability of choosing the main exit under the main exit principle

The parameters used in the evacuation simulation of this study are divided into three categories:

1. Joint-Rental Exclusive Parameters: This includes the probabilities of the three evacuation behaviors chosen under the joint-rental relationship, the delay time for choosing the delay evacuation behavior, the duration of stay at the second target point in the return evacuation behavior, and the range of values for the sum of reaction and preparation time;
2. Family Exclusive Parameters: This includes the reaction time of individuals before gathering in the group evacuation behavior, the deliberation time after gathering and before departure, and the range of values for the sum of reaction and preparation time;
3. General Parameters: This includes the time from the occurrence of the event to the issuance of the warning notification, determined by the type of alarm equipment in the residential area itself and the probability of exit choice under the main exit principle.

The value of the parameter comes from the "Questionnaire on pre-evacuation behavior of community residents in an emergency" in reference [3].

4. Evacuation Simulation and Results

The evacuation simulation and result analysis of this study are based on the following premises:

(1) The proportion of rental structures within residential buildings is subject to complex socio-economic dynamics. This study analyzes the results solely from the perspective of emergency evacuation safety;

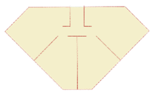
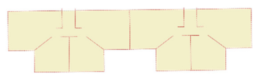
(2) Individuals living alone or elderly individuals with limited mobility significantly affect the evacuation process. The population census data used are accurate only to the level of each residential building, with assumptions made based on averages. Therefore, evacuation strategies for other relationships were not considered;

(3) Specifically, this study acknowledges that factors such as different family types with elderly members, individuals with mobility/vision/hearing impairments, and children, as well as the psychological impacts and fear affecting residents on higher floors, can significantly influence evacuation dynamics. However, due to privacy concerns and the accuracy of the population census data only to the overall number of residents in each building, these factors are not considered in this study;
(4) This study focuses on the influence of interpersonal relationships on exit choice time. The evacuees are assumed to be residents who have lived in the community for a period of time and are familiar with the location of the main exits and the paths to these exits. Therefore, the spatial layout of the building environment and its complexity are not considered in this study;
(5) While it is possible that social media or online chat platforms could notify residents to evacuate more quickly, the Changhongfang community only has a unified WeChat owner group and lacks a unified group of residents who actually live in the community. Additionally, the accuracy and authority of the messages posted, as well as the timely reception by all members, are unpredictable. Therefore, this study does not consider the impact of social media and online chat platforms on evacuation.

4.1. Maximum Ratio of Joint-Rental Population within Buildings

The buildings are categorized into four types based on their number of floors and layouts: (a) four buildings with four stories following layout pattern 1; (b) three buildings with five stories following layout pattern 1; (c) three buildings with six stories following layout pattern 1; and (d) eight buildings with six stories following layout pattern 2, as shown in Table 5.

Table 5. Detailed information on four different buildings.

Story Type	**4-Story**	**5-Story**	**6-Story**	
Layout Model		Pattern 1		Pattern 2
Illustration				
Number of buildings	4	3	3	8
Maximum number of people	56	65	74	130

In this section, buildings with a maximum number of people from each kind will be used to simulate the suggested maximum ratio of joint-rental people. We selected this four-story building with 56 people living inside as an example, implementing evacuation simulation under different proportions of joint-rental and family residents; the evacuation time is shown in Table 6.

Table 6. Evacuation time under different proportions of joint-rental and family residents.

Proportion	**Family (100%)**			**Joint-Rental (25%) Family (75%)**			**Joint-Rental (100%)**		
Evacuation Time (s)	298.13	298.22	298.39	357.47	356.69	360.11	391.76	365.31	361.12
Average Evacuation Time (s)	298.24			358.09			372.73		

The evacuation times for each proportion show three different values because the evacuation parameters in this study are provided as ranges rather than fixed values. As a result, the outcomes of each evacuation simulation vary. To eliminate random occurrences and improve the model's accuracy and adaptability, each evacuation simulation was conducted three times. As per the "Codes of Fire Protection Design for Chinese Buildings", the permissible duration for the safe evacuation of typical residential buildings should be under 360 s. Consequently, within the Changhongfang community, the maximum proportion of the rental population within four-story residential buildings is set at 25%.

Following the same method, the spatial distribution of SDR inside other buildings is shown in Figures 16–19.

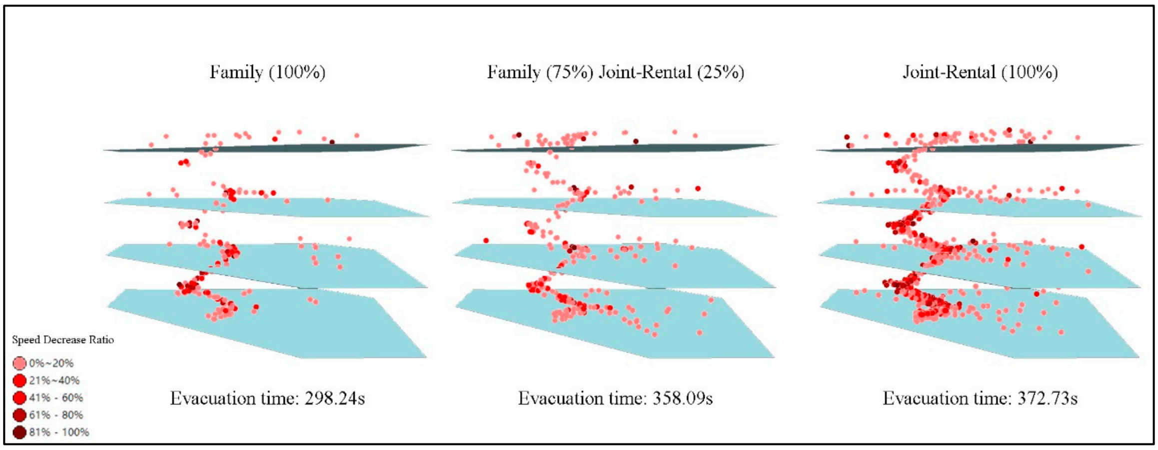


Figure 16. SDR in 4–story with maximum people under different family and joint-rental ratio.

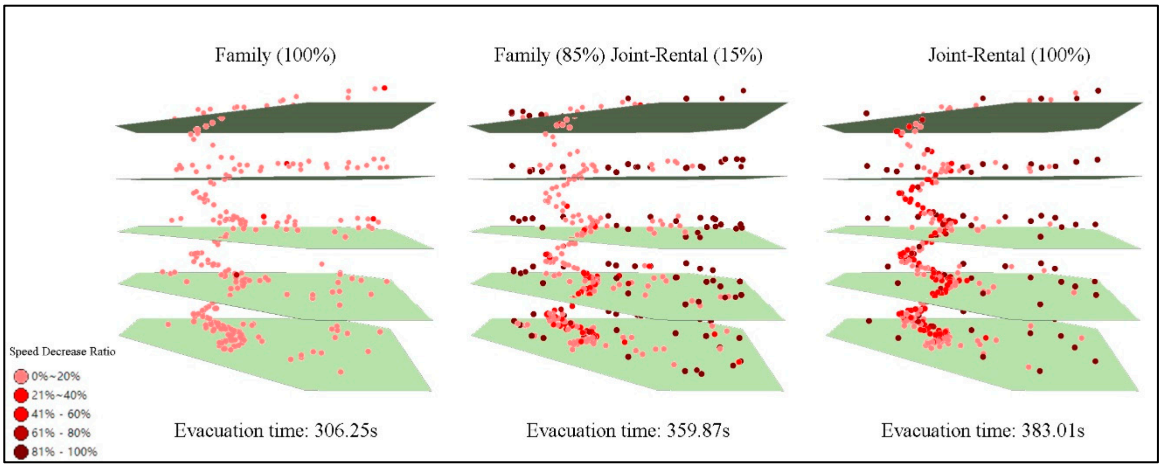


Figure 17. SDR in 5–story with maximum people under different family and joint-rental ratio.

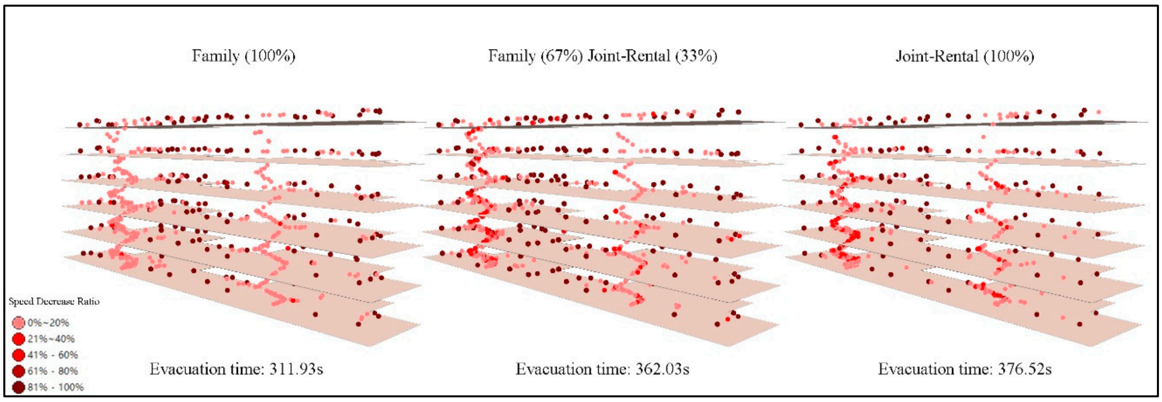


Figure 18. SDR in 6–story model 1 with maximum people under different family and joint-rental ratio.

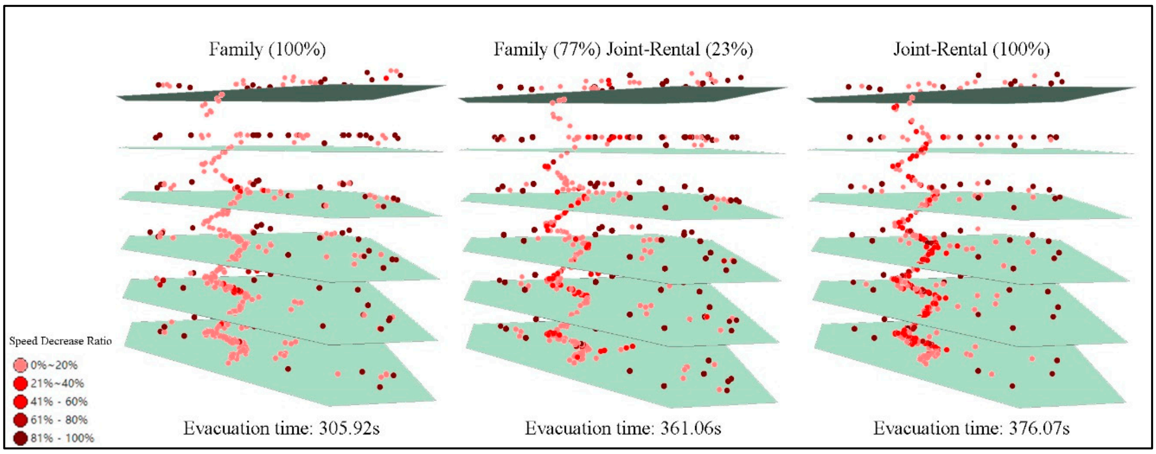


Figure 19. SDR in 6–story model 2 with maximum people under different family and joint-rental ratio.

From Figures 16–19, it is evident that under emergency situations, residents with joint-rental relationships have longer evacuation times compared to those with family ties. Consequently, the overall evacuation time is directly proportional to the percentage of residents with joint-rental relationships within a building. When the overall evacuation time extends to approximately 6 min (or 360 s), the corresponding percentage of joint-rental residents indicates the upper limit of the joint-rental ratio for that structure. This upper limit can vary depending on the building's height and internal architecture. As a result, the maximum joint-rental ratios for the four building types within the study area differ accordingly. The suggested max ratio of joint rental for each building is listed in Table 7.

Table 7. Suggested max ratio of joint rental for each different building.

Story Type	4–Story	5–Story	6–Story	
Suggested max ratio of joint rental	25%	15%	33% (Model 1)	23% (Model 2)

4.2. Impact on Road Evacuation Efficiency under Different Exits Selection Principles

In this section, evacuation simulations were implemented on the road network of the Changhongfang community under the "Main-Exit" and "Near-Exit" principles separately. SDR was used to indicate the degree of crowdedness in these simulation results, as shown in Figures 20 and 21.

From Figures 20 and 21, the following observations can be made:

a. Regarding evacuation time, when residents share similar relationships, the evacuation time for residents of Changhong Square under the "Near-Exit" principle is significantly shorter than that under the "Main-Exit" principle. Specifically, when all residents have familial ties, the time is reduced by 114.87 s (a decrease of 19.8%). For conditions where all residents are in joint-rental relationships, the time is shortened by 245.41 s (a reduction of 32.3%);

b. In terms of road congestion within the residential area, under similar resident relationships, the congestion level under the "Near-Exit" principle is considerably less than under the "Main-Exit" principle. Notably, under the "Main-Exit" principle, roadway congestion is more severe when all residents have family ties compared to when all are in joint-rental situations. This is attributed to the tendency of residents with family ties to choose evacuation routes that allow them to congregate with their family members.

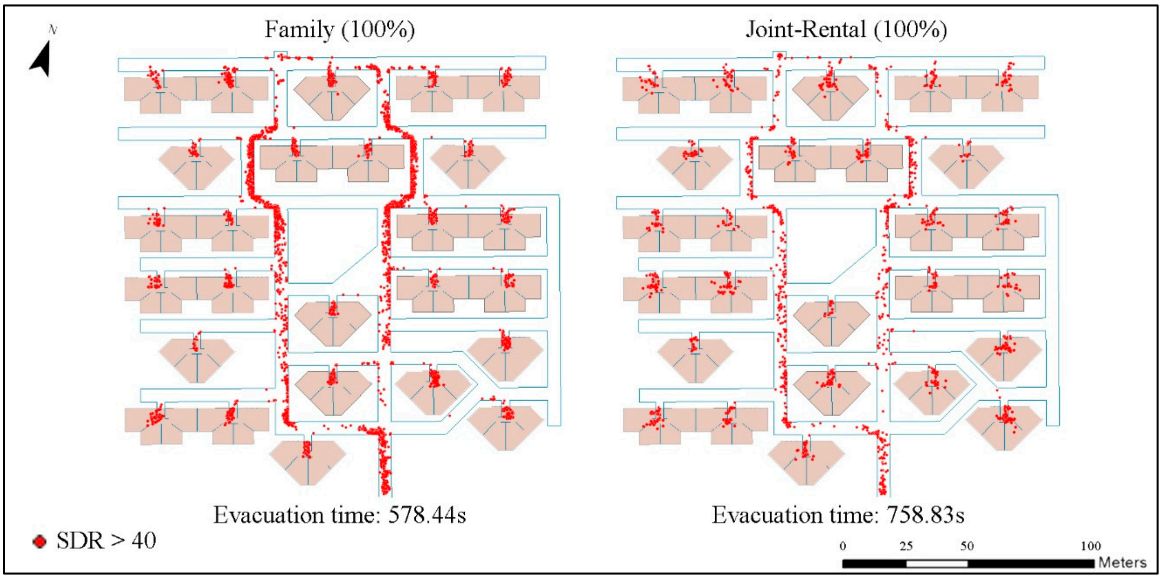


Figure 20. Spatial distribution of SDR on community roads under "Main-Exit" principle.

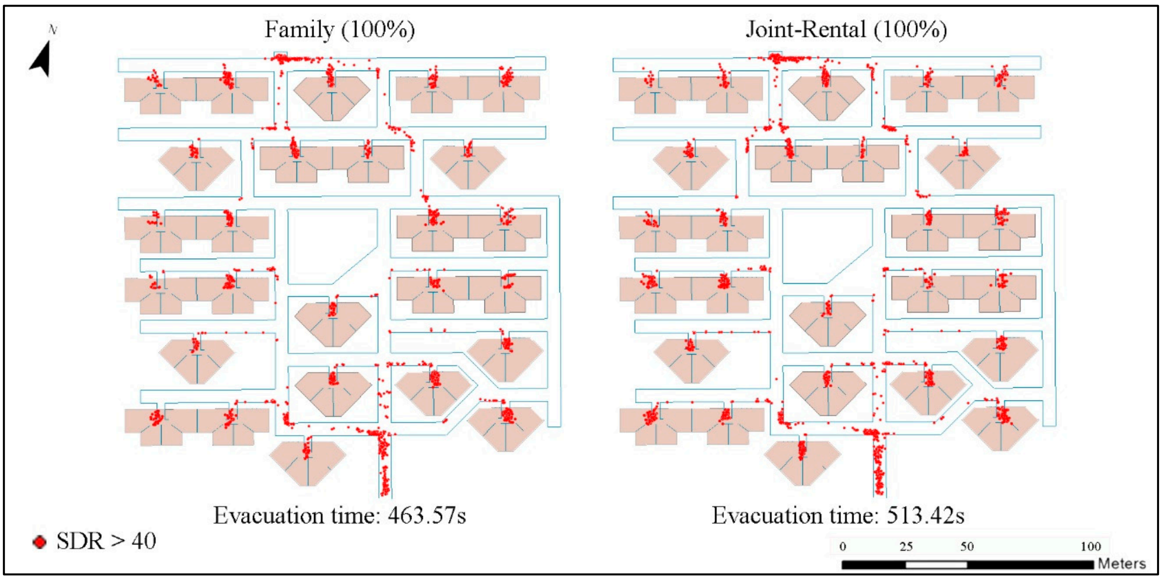


Figure 21. Spatial distribution of SDR on community roads under "Near-Exit" principle.

5. Enhanced Strategies for Evacuation Optimization

Indoor areas: For residential buildings with a cohabitation ratio below the maximum recommended threshold, community managers should control the number of rentals to ensure that it does not exceed this threshold. For buildings where the cohabitation ratio exceeds the maximum recommended threshold, community managers should enhance evacuation training for renters, strengthen neighborly connections, and assign older residents as evacuation guides for small groups. This approach aims to make cohabitation and family relationships more cohesive.

Outdoor: To enhance the efficiency of evacuation processes, several outdoor measures are recommended. First, ensuring that non-main entrances are kept open regularly can provide additional escape routes, reducing congestion and facilitating quicker evacuations. Second, installing clear and visible exit guidance signs at road intersections can help direct evacuees to the safest and most efficient routes, minimizing confusion during emergencies. Lastly, planning new parking spaces strategically can prevent vehicles from obstructing evacuation paths and ensure that emergency services have unobstructed access to critical areas. These measures collectively aim to improve the overall safety and effectiveness of evacuation procedures in residential communities.

6. Discussion and Limitations

Based on the simulation results, numerous comprehensive discussions can be presented as follows:

(1) Under the same conditions, the crowded degree of joint-rental tenants inside the building is much higher than that of family-tie members (Figures 13–16). The possible reason is that family members evacuate as a whole, and the speed remains more stable compared to discrete joint-rental tenants;
(2) Under the same conditions, the evacuation time of joint-rental tenants in buildings is also higher than that of family members (Figures 17 and 18). The possible reason is that joint-rental tenants with independent living conditions need to spend more time confirming emergencies and responding;
(3) The maximum ratio of joint-rental tenants that can be accommodated in the building is determined by the number of floors and layout co-determination (Table 6); residential area managers should focus on the rental situation of five-story residential buildings, with the largest ratio of joint-rental tenants being only 15%;
(4) The level of familiarity with the community varies between joint-rental tenants and family members. Joint-rental tenants who are not yet familiar with the community are likely to choose an exit based on the "Main Exit" principle, while family members who are more familiar with the community are likely to choose an exit based on the "Near Exit" principle. The former results in longer evacuation time and greater personnel congestion compared to the latter (Figures 17 and 18). Therefore, it is necessary for community management personnel to provide exit prompts and guidance on the community roads.

While this study provides foundational insights, it also acknowledges certain limitations that suggest avenues for further research. Primarily, the agent-based models employed in this analysis do not encompass all demographic segments, notably excluding individuals with limited mobility or other physical constraints that significantly alter evacuation dynamics. Moreover, this simplification omits the complex, real-world interactions and decision-making processes that may occur in such scenarios, including the spontaneous formation of assistance groups, the role of emergency personnel, and the potential for ad-hoc changes in environment configurations, all of which can materially impact evacuation outcomes. Future iterations of this research will aim to address these limitations by integrating more comprehensive demographic data, improving the granularity of agent typologies, and possibly introducing adaptive components that better reflect the fluid dynamics of real-world emergency evacuations.

The unique socio-economic and cultural characteristics of the Changhongfang community may not be reflective of other regions in China or other countries. As a result, the conclusions drawn from this case study may have limited generalizability to different cultural or regional contexts. We recommend that future research consider these variations to ensure the broader applicability and relevance of the findings.

Furthermore, we acknowledge that one of the limitations of our study is that it does not address other significant factors, such as the unique challenges faced by individuals living alone or those with limited mobility. These factors can strongly influence the evacuation process. Future research should explore these aspects to provide a more comprehensive understanding of the varied dynamics involved in evacuation scenarios. This would help ensure that evacuation plans are inclusive and effective for all members of the community.

7. Conclusions

Within urban residential areas, family-tie and joint-rental relationships are the predominant forms of interpersonal connections among residents. During emergencies, these differing interpersonal dynamics inevitably lead to distinct evacuation strategies, significantly impacting evacuation efficiency. Additionally, the choice of exit selection principles during emergency evacuations can considerably influence the congestion levels on residential area roads. The primary objective of this study is to investigate the extent to which varying proportions of resident interpersonal relationships, combined with different exit selection efficiencies, affect both the evacuation efficiency and the congestion levels within residential areas.

This study explores the feasibility of the proposed models by conducting a comprehensive case study in the Changhongfang residential community located in Xuhui District, Shanghai, China. The research methodology unfolded in three distinct phases. Initially, leveraging Building Information Modeling (BIM), a three-dimensional representation of the residential area was constructed, providing a comprehensive visualization of the spatial context. Subsequently, this study integrated the distinct evacuation behavior characteristics observed among individuals with family-tie and joint-rental relationships, recognizing the variability in evacuation responses among different occupant groups. This integration aimed to capture the nuanced behavioral patterns that could influence evacuation efficiency in emergency situations, along with the principles of exit selection, an intelligent agent model for resident evacuation within the community was developed. Finally, through grouped experiments considering varying proportions of interpersonal relationships and the two exit selection principles, the following conclusions were drawn: 1. For the four types of buildings within the residential area (four-story, five-story, six-story Model 1 and six-story Model 2), the recommended maximum joint-rental ratios are 25%, 15%, 33%, and 23% respectively; 2. The "Main-Exit" selection principle results in reduced evacuation efficiency and heightened roadway congestion.

The primary advantages and contributions of this study are twofold: (1) The maximum joint-rental ratio for various buildings was determined by considering the distinct evacuation behaviors of joint-rental tenants and family members; (2) This study compared and assessed the impact of two different exit selection principles on evacuation efficiency.

8. Future Outlook

We intend to share the insights gained from this research with local emergency management authorities. This collaboration aims to leverage our findings to improve the coordination and planning of evacuation strategies, thereby enhancing overall emergency response efforts. By integrating our research outcomes into practical applications, we believe we can significantly benefit local communities.

We recognize the potential benefits of developing an application to improve evacuation efficiency and effectiveness in urban contexts. Therefore, we plan to explore the possibility of creating a mobile application that incorporates our simulation scenarios. This app could provide personalized, real-time guidance during emergencies, thereby enhancing the practical impact of our research.

Going forward, this study will consider applying for on-site evacuation drills to validate the evacuation simulation results. However, given the high cost of conducting on-site drills, the inevitable difference in residents' reactions during a drill compared to a real emergency, and the impracticality of conducting multiple drills to eliminate randomness, computer software simulations remain the most economical and practical solution for related research.

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