

Modeling and Study of Companion Behavior in Fire Evacuation of Commercial Complexes Using Cellular Automata

Bo Li, Xiangyang Liu

Abstract—Companion behavior during fires in commercial complexes is a key factor affecting emergency evacuation efficiency. This study develops a cellular automaton (CA) model that integrates individual speed differences, dynamic physical energy consumption, and recovery mechanisms to simulate pedestrian evacuation in this context. By coupling environmental familiarity, fire visibility, and two conflict resolution strategies, the study quantifies the impact mechanisms of the proportion of independent individuals, group size, and composition on evacuation efficiency. The results indicate that increasing the proportion of independent individuals effectively alleviates congestion, whereas larger groups significantly delay the evacuation process; areas dominated by young adults exhibit the highest evacuation efficiency; in high-density environments, adopting a conflict resolution strategy that prioritizes vulnerable groups can enhance overall efficiency; the positive effect of environmental familiarity decreases as population density increases; the effect of visibility on evacuation efficiency shows significant density dependence, where it is beneficial in low-density situations but less effective in medium-to-high-density environments. This study reveals the complex dynamic mechanisms of companion behavior in fire evacuation, and its findings can provide critical parameters for emergency evacuation management.

Index Terms—Companion behavior; Fire evacuation; Cellular automata; Heterogeneous population; Conflict resolution strategy; Environmental familiarity; Visibility.

I. INTRODUCTION¹

With the rapid advancement of urbanization, commercial complexes have emerged as key hubs for urban consumption and social interaction. Characterized by complex spatial layouts, high pedestrian density, and diverse functional zones, these buildings effectively meet modern lifestyle demands. However, their heterogeneous occupant composition also presents significant challenges for evacuation during fire emergencies and other unforeseen incidents.

The efficiency of pedestrian evacuation is not only crucial to individual life safety but also directly determines the resilience of architectural spaces. Among various analytical approaches, microscopic simulation methods have become prevalent due to their ability to capture pedestrian behavioral

logic with high precision. In particular, the CA model [1] has been widely adopted in evacuation simulations for its flexible state definition, customizable movement rules, computational efficiency, and strong reproducibility. Researchers have continuously extended the CA model from multiple perspectives. At the level of pedestrian movement mechanisms, the model's realism has been improved by refining pedestrian step length [2] and speed variation processes [3]. Through constructing heterogeneous field models and incorporating environmental perception parameters, pedestrian behaviors such as avoidance [4], detouring [5], and pushing [6] have been reproduced to examine their influence on the overall evacuation process. Regarding pedestrian heterogeneity, the model has been applied to scenarios involving luggage-bearing individuals [7,8], children [9,10], and people with special needs [11], while also accounting for psychological traits [12,13], fire hazard exposure [14], and intoxication states [15] that affect evacuation decisions. In terms of specific architectural environments, targeted simulations and optimizations have been conducted for high-rise buildings [16], spaces with multiple obstacles [17,18], and public transportation facilities [19,20].

In studies of fire evacuation in commercial complexes, visibility is recognized as the primary environmental factor influencing pedestrian decision-making, often exerting a greater impact than temperature or toxic gases. Neto et al. [21] identified visibility reduction caused by smoke as a key indicator for determining safe evacuation conditions. Environmental familiarity is also a critical variable. Individuals who are familiar with the environment can quickly identify exits and optimize their route choices, while unfamiliar individuals tend to become disoriented or exhibit herd behavior [22]. This phenomenon is particularly pronounced in commercial complexes with complex spatial configurations. Group behavior, a common pattern in such environments, may enhance local evacuation efficiency through mutual coordination, but it can also intensify congestion due to the constraints of synchronized movement. This behavioral mechanism has become a critical gap restricting the optimization of emergency evacuation in commercial complexes. Rastogi et al. [23] observed that small groups of more than three individuals tend to split into subgroups of two or three members. Qiu et al. [24] modeled the effects of intragroup structure and intergroup relationships on crowd behavior. Song et al. [25] incorporated parameters such as environmental familiarity and guidance effects into a CA-based group evacuation model. Mao et al. [26] developed an emotion

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contagion-based model to simulate companion decision-making during emergency evacuations, while Chen et al.[27] proposed a group evacuation model considering auditory guidance and wall-following behaviors. However, existing studies have yet to thoroughly explore the categorization of group behaviors and the behavioral characteristics of heterogeneous populations. In particular, within commercial complexes, group compositions are highly diverse, and a systematic analytical framework remains lacking.

In summary, this study aims to address fire evacuation scenarios in commercial complexes by developing a CA model that incorporates individual speed differences, physical energy consumption, and recovery mechanisms. The model will include environmental familiarity, fire visibility, and two conflict resolution strategies, with a focus on the behavior mechanisms and overall impacts of 2~3 person companion groups during evacuation, aiming to provide theoretical basis and strategic support for emergency evacuation management in commercial complexes.

II. MODEL CONSTRUCTION

A. Heterogeneous Population Setup

In the complex spaces of commercial complexes, which integrate various functions, the population is notably heterogeneous, including young and middle-aged adults who move quickly and flexibly, as well as vulnerable groups with slower movement. To reflect realistic evacuation scenarios, this study categorizes the population into four groups: adult males, adult females, elderly individuals, and children, with their basic evacuation speeds set at 1.4 m/s, 1.2 m/s, 0.8 m/s, and 0.9 m/s, respectively, as outlined in [28]. In such spaces, pedestrian movement paths often intertwine, and the crowd density fluctuates, with companion behavior being particularly prevalent and varied. These behaviors range from companions traveling together, colleagues collaborating, to families evacuating together. The combinations of individuals with different ages, genders, and physical capacities directly influence group movement efficiency and evacuation decisions.

To systematically reflect typical companion patterns in the fire evacuation scenario of commercial complexes, this study defines eight group types: including four types of 2-person groups, four types of 3-person groups, and individuals evacuating independently, as shown in Table 1. This classification takes into account differences in group size as well as combinations of members with varying physical capabilities. Each group is set to move at the speed of its slowest member. This classification allows for an effective capture of the impact mechanisms of different companion types on group movement and the evacuation process in complex commercial environments.

Table 1 Composition of Companion Groups.

Group	Group Size	Group Composition	Speed-Limiting Member	Speed
g1	2	Adult Male + Adult Male	Adult Male	1.4m/s
g2	2	Adult Male + Adult Female (or Adult Female + Adult Female)	Adult Female	1.2m/s

g3	2	Adult Male + Child (or Adult Female + Child)	Child	0.9m/s
g4	2	Elderly + Child	Elderly	0.8m/s
g5	3	Adult Male + Adult Male + Adult Male	Adult Male	1.4m/s
g6	3	Adult Female + Adult Female + Adult Female	Adult Female	1.2m/s
g7	3	Adult Male + Adult Female + Child (or Adult Male + Adult Male + Child)	Child	0.9m/s
g8	3	Elderly + Child + Child (or Elderly + Elderly + Child)	Elderly	0.8m/s
g9	1	Independent Evacuation	---	---

During evacuation, the change in physical strength of individuals plays a critical role in affecting evacuation efficiency. Prolonged movement, physical exhaustion in congested environments, and subsequent physical recovery significantly impact both individual and group mobility, especially for vulnerable groups such as the elderly and children. Therefore, this study incorporates a mechanism for physical consumption and recovery to simulate evacuation behavior more realistically. The initial physical energy of all individuals is set within the range [0, 1], and based on literature [29], the initial maximum physical state is defined as shown in Table 2, with adult males having the highest energy reserves and the elderly having the lowest physical baseline. The physical mechanism centers on the member whose speed is constrained, forming the core of the group's coordination. Two physical thresholds are set to control the group's speed. If any member's physical strength falls below the lower threshold w , the group's speed is reduced to 60% of its initial speed, indicating fatigue [30]; once the physical strength recovers to the upper threshold r , the speed returns to its initial value. The lower threshold for the elderly is set at 0.4, meaning their physical strength is more likely to drop below the critical point, leading to fatigue, and their recovery threshold is set at 0.7, indicating greater difficulty in recovery. This aligns with the characteristics of rapid physical decline and slow recovery in older adults. For children, w is set at 0.35 and r at 0.65, both higher than for adult males and females, reflecting their relatively weaker physical stability.

In terms of physical consumption and recovery rates, elderly individuals have higher metabolic costs during movement, consuming about 10%~30% more energy per meter than younger individuals[31]. Children, on the other hand, have a stronger metabolic recovery ability and recover more quickly after short, intense activities[32]. Fatigue and recovery rate are positively correlated; the greater the exercise load, the longer the VO_2 recovery time [33]. Based on the CA model implemented in MATLAB, the physical energy consumption rates for the four groups are set as follows: "older adults = 0.035 > children = 0.03 > adult females = 0.025 > adult males = 0.02." This gradient reflects the reality that vulnerable groups, such as the elderly, tire more easily during movement. The recovery rates are set as: children = 0.045 > adult males/females = 0.04 > elderly = 0.035, which not only reflects the faster recovery of children

after rest but also highlights the slower recovery of the elderly due to their physiological characteristics.

Group movement follows the principle of synchronization, where the individual consumption and recovery of physical strength proceed autonomously. However, the overall movement state of the group depends on the physical status of all its members. This mechanism is in line with human physiological laws and can accurately

capture the dynamic effects of the "fatigue-recovery" cycle on group movement efficiency during evacuation. For example, the group may continuously slow down as elderly members tire, or children may rapidly regain strength after a short rest, thus accelerating the overall progress. This enhances the realism of the simulation and provides a more reliable theoretical basis for evacuation research involving heterogeneous populations within the complex.

Table 2 Physical Consumption and Recovery Mechanism.

Person	Initial	Fatigue	Max	Lower Limit	Recovery	Physical	Physical
Type	Speed	Speed (v_2)	Energy	Threshold (w)	Upper Limit	Consumption	Recovery
	(v_1)		($energy$)		(r)	Rate (a_1)	Rate (a_2)
Adult Male	1.4m/s	0.84m/s	1.00	0.30	0.60	0.02	0.04
Adult Female	1.2m/s	0.72m/s	0.95	0.30	0.60	0.025	0.04
Elderly	0.9m/s	0.54m/s	0.90	0.35	0.65	0.03	0.045
Children	0.8m/s	0.48m/s	0.80	0.40	0.70	0.035	0.035

(3)

B. Model Description

A multi-type pedestrian evacuation CA model is developed based on the field model, considering the companion behavior of heterogeneous populations. The model employs a Moore neighborhood structure, as shown in Fig. 1, with each cell sized at 0.4m×0.4m. Each pedestrian occupies one cell, and the state of each cell can be one of three types: empty, occupied by a pedestrian, or occupied by an obstacle. Pedestrians move with a certain transition probability to one of the eight neighboring cells or remain stationary. The model incorporates the four aforementioned types of pedestrians.

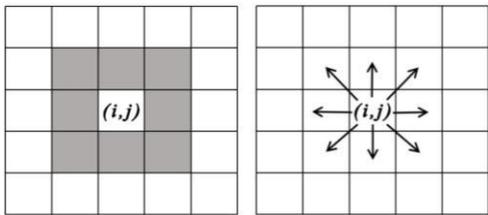


Fig.1 Moore neighborhood

During the evacuation process, pedestrians select neighboring empty cells to move to with a certain probability. P_{ij} represents the transition probability of cell (i, j) , and the calculation formula is as follows:

$$P_{ij} = N \exp(k_s S_{ij})(1 - n_{ij}) \varepsilon_{ij} \quad (1)$$

In the equation, N is the normalization coefficient; k_s represents the static field parameter, where $k_s \in [0, \infty]$, and S_{ij} represents the static field used to quantify the attractiveness of the exit, which increases as the distance to the exit decreases. When obstacles are present, the shortest path length determined by the Dijkstra algorithm is used as the value of the static field. The coordinates of the current cell are denoted as i, j ; n_{ij} and ε_{ij} are the cell state parameters. If the cell is occupied by an obstacle, $n_{ij} = 1$, otherwise it is 0. If the cell is occupied by a pedestrian, $\varepsilon_{ij} = 0$ otherwise it is 1.

$$N = \left[\sum_{ij} \exp(k_s S_{ij})(1 - n_{ij}) \varepsilon_{ij} \right]^{-1} \quad (2)$$

$$S_{ij} = \max_{(i,j)} \left\{ \min_{(i_{ek}, j_{ek})} \sqrt{(i_{ek} - i)^2 + (j_{ek} - j)^2} \right\} - \min_{(i_{ek}, j_{ek})} \sqrt{(i_{ek} - i)^2 + (j_{ek} - j)^2}$$

In the equation, (i_{ek}, j_{ek}) denotes the coordinates of the exit, where $k=1,2$.

To more accurately simulate the information disparity during the evacuation process in a fire scenario, the environment familiarity parameter σ and the fire visibility variable are introduced. The dense smoke generated by the fire significantly reduces spatial visibility, thereby severely affecting the ability of individuals to recognize paths and make decisions [21]. The environment familiarity parameter is used to represent a pedestrian's level of familiarity with the building, with a value range of $[0,1]$, where 0 indicates complete unfamiliarity with the environment and 1 indicates full familiarity. A value between 0 and 1 represents increasing familiarity with the environment. Visibility is represented by the number of cells R , with $R = 1$ corresponding to a 0.4m field of view. In the simulation, pedestrians familiar with the environment will always follow the shortest path to the exit, guided by the static field. Pedestrians unfamiliar with the environment, however, will adopt a conformist evacuation strategy[22] under conditions of limited fire visibility, following the movement direction of pedestrians familiar with the environment within their field of view. Specifically, these pedestrians will move in the direction with the highest number of pedestrians familiar with the environment within their field of view R . If multiple directions have the same number, they will choose randomly. The probability of a pedestrian unfamiliar with the environment moving to the next cell is defined as:

$$P_m = L_m \left(\sum_{m=1}^8 Y_m \right)^{-1} \quad (4)$$

In the equation, m represents the 8 possible movement directions of the cell, with a value range of $[1, 2, \dots, 8]$; L_m is the number of pedestrians that can be chosen to follow in a specific direction within the visibility range; Y_m represents the total number of pedestrians in a specific direction within the visibility range.

C. Conflict Resolution Strategies

To resolve conflicts arising from multiple groups competing for the same cell target position, two conflict resolution strategies have been designed based on differences

in group mobility abilities. Both strategies assign differentiated success probabilities for competition among different groups. The groups are classified into those containing children ($h1$), the elderly ($h2$), females ($h3$), and other groups ($h4$). Conflict Resolution Strategy 1 prioritizes the evacuation of faster-moving groups, with competition probabilities set as $h1=0.1 < h2=0.2 < h3=0.3 < h4=0.5$, meaning that groups with stronger physical abilities have a more significant competitive advantage. Conflict Resolution Strategy 2 prioritizes the protection of vulnerable groups, with probabilities set as $h1=0.5 > h2=0.3 > h3=0.2 > h4=0.1$, increasing the competition weight for children, the elderly, and other groups, simulating yielding behavior during the evacuation process. When conflicts arise between groups of the same type, a random selection mechanism is used to determine the successful group, and the group that loses the competition remains in its original position. This simulates the conflict resolution process under different priority logics.

D. Evolution Update Rules

The model employs a parallel update rule to update the positions of all pedestrians in the scenario, with each time step being 0.3 seconds. The update rules are as follows:

- (1) Initialize the distribution of pedestrians based on the predefined proportions of the four types of individuals, group formation probabilities, and initial density;
- (2) After the evacuation starts, each group moves according to the corresponding rules. Pedestrians gradually expend physical strength during movement, slowing down and gradually recovering strength when it falls below a threshold;
- (3) Pedestrian movement is differentiated based on environmental familiarity, and the next position is calculated by combining the transfer probability formula;
- (4) If multiple groups compete for the same cell, competition probabilities are assigned according to the established conflict resolution strategy. The successful group occupies the cell, and the losing group remains in its original position;
- (5) Update the pedestrian positions for the next time step and remove those who have reached the exit from the scenario;
- (6) Repeat steps (2) to (5) until all pedestrians have evacuated, ending the simulation.

III. SIMULATION AND RESULTS ANALYSIS

The simulation scenario is set as a 30m×20m rectangular area with two exits, as shown in Fig. 2. The corresponding cell grid size is 75×50, and the boundary of the area is defined by walls. Both exits are located on the left side, each with a width of 2 meters, corresponding to 5 cells. A successful evacuation is considered when pedestrians reach the exit. To minimize random errors, each experimental group is simulated 50 times, and the average evacuation time is taken as the final result.

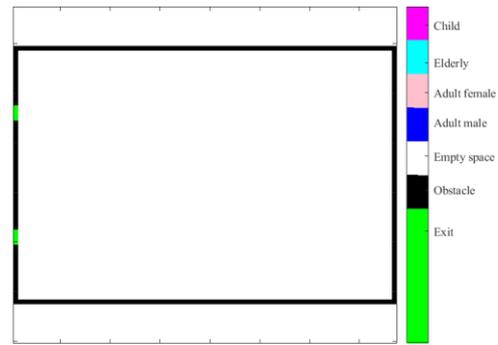


Fig. 2. Evacuation Scenario

A. Analysis of the Impact of Group Structure on Evacuation

① The Effect of Independent Individuals' Proportion on Evacuation

The effect of the proportion of independent individuals on evacuation efficiency is studied without considering environmental familiarity and fire visibility. The initial pedestrian densities are set as $\rho_1=0.2, \rho_2=0.4, \rho_3=0.6, \rho_4=0.8, \rho_5=1.0$, and Fig.3 shows the variation of evacuation time with the proportion of independent individuals at different densities. The results indicate that when the proportion of independent individuals is fixed, the evacuation time increases with rising pedestrian density. Under the same density, the evacuation time generally decreases as the proportion of independent individuals increases. Moreover, the higher the density, the more pronounced the improvement in evacuation efficiency contributed by independent individuals. These findings are consistent with those of reference [34], in which an Agent-based model was developed using an improved Social Force Model and simulated through AnyLogic.

Data observations show local drops in evacuation time at independent individual proportions of 10% and 20%. This phenomenon is caused by the self-organizing flow line reconstruction triggered by the interaction between independent individuals and groups. A small number of independent individuals can break local deadlocks and optimize the flow configuration, thus temporarily increasing the exit throughput. The higher the density, the greater the proportion of independent individuals required to trigger this effect. The speed heterogeneity and flexibility of independent individuals help improve intercalation efficiency at a specific proportion, while differences in group space occupation and coordination abilities at different densities also influence the location of the turning point. When the pedestrian density is too high, independent individuals can no longer play a guiding role, and thus no turning point is observed.

Fig. 4 shows the evacuation count over time at different proportions of independent individuals. The number of evacuees at the same time step increases as the proportion of independent individuals increases, with all proportion groups showing a characteristic of efficient increase in the early stage followed by a slower increase in the later stage. This is because in the early stage, there are sufficient spatial resources, and independent individuals have a significant advantage in flexibility, allowing them to quickly bypass obstacles formed by groups. In the later stage, pedestrians continue to gather toward the evacuation bottleneck at the

exit, the space becomes saturated, and the flow of people becomes dense, reducing the flexibility advantage. This further suggests that independent individuals can improve evacuation efficiency at various stages by enhancing path flexibility and reducing group coordination time, thereby shortening overall evacuation time while effectively alleviating the inhibiting effect of later-stage spatial congestion on evacuation speed.

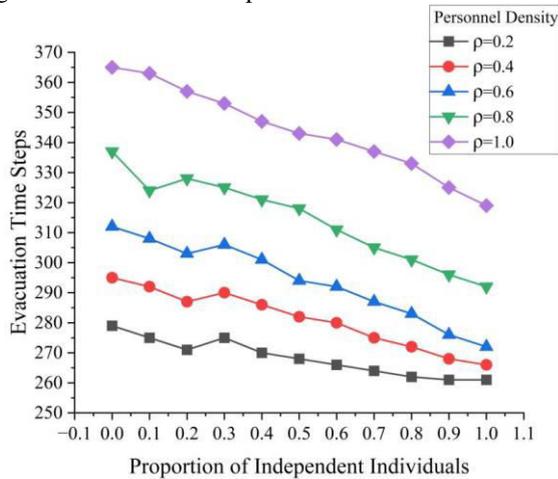


Fig. 3. Relationship between Evacuation Time and the Proportion of Independent Individuals

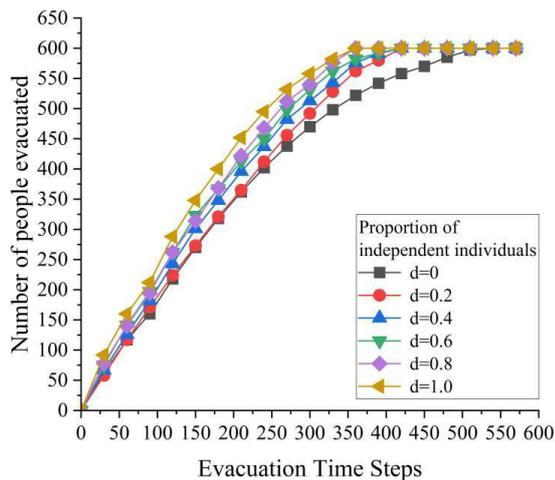


Fig. 4. Evacuation Population Change over Time

② The Impact of Group Size on Evacuation

A no-independent individual evacuation environment is constructed to study the effect of group member size on evacuation efficiency by adjusting the proportion of 2-person and 3-person groups, as shown in Fig. 5. The results show that as the proportion of 3-person groups increases, evacuation time tends to increase, but the increase is relatively small. 3-person groups, due to their large space occupation and low mobility, are prone to causing local congestion at bottleneck areas such as corridors or exits, thereby affecting the continuity of overall movement. Additionally, they take more time to adjust their formation, resulting in poor passage continuity. In contrast, 2-person groups are more likely to advance through gaps in the crowd or quickly switch their formation, resulting in higher movement efficiency. The gradual increase in evacuation time is mainly due to the ideal experimental conditions, with stable group composition, no environmental familiarity

differences, low decision-making delays, and basic cooperation among group members. The increase in conflict is limited, and the difference in movement efficiency does not significantly expand. In actual scenarios, where group composition is more chaotic, environmental familiarity is low, and cooperation is poor, an increase in the proportion of 3-person groups may lead to more significant evacuation delays.

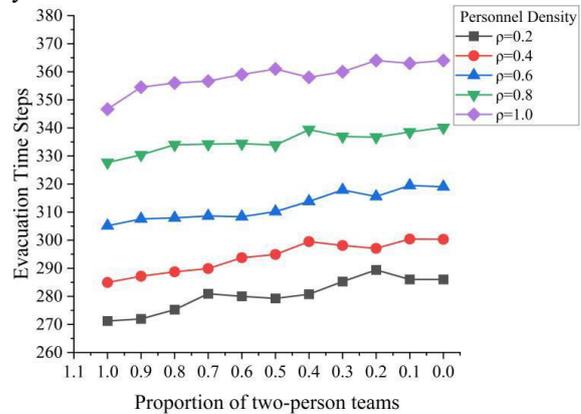


Fig. 5. Relationship between the Proportion of Two-person Groups and Evacuation Time

③ Impact of Group Types on Evacuation

To improve the scientific allocation of experimental groups, the evacuation abilities of different types of individuals must first be evaluated. Reference[35] introduces a multi-criteria evaluation method, focusing on the base speed and physical characteristics of adult males, adult females, elderly individuals, and children. The model combines positive indicators (v_1 , $energy$, a_2) and negative indicators (w , r , a_1), constructing a composite ability weight calculation model. The formula calculates the ratio of the product of positive indicators to the product of negative indicators, with a larger value indicating stronger overall evacuation capability. After calculation and normalization, the weights for the four types of individuals are determined as 0.47 for adult males, 0.3 for adult females, 0.16 for children, and 0.07 for the elderly. These weights reflect the contribution of each group to the overall evacuation efficiency, providing a quantitative basis for group allocation. Based on these weights, the group allocation percentages are defined in accordance with the experimental group characteristics, following a "dominant-auxiliary-marginal" three-tier logic. The dominant group comprises 70% of the total, emphasizing core features, the auxiliary group makes up 20%, selecting reasonably associated groups, and the marginal group accounts for 10%, representing underrepresented groups in the scenario. Under the constraint of total group size, groups are allocated proportionally to $g_1 \sim g_8$. After fine-tuning, a balanced distribution scheme is formed, combining both quantitative reasonableness and scene representativeness, as shown in Table 3. The comprehensive area serves as a benchmark control, covering all types of individuals. The young adult-dominant area centers on combinations of adult males and females, simulating a workday scenario with concentrated young adult traffic. The parent-child dominant area focuses on the combination of "adult male/adult female/elderly + child," simulating a scene of parents shopping with children. The elderly-dominant area centers on

combinations of “elderly + children/adult male/adult female,” simulating a scenario of elderly individuals with grandchildren or relaxing alone. The composite ability weight L calculation formula is as follows:

$$L = \frac{v_1 \times energy \times a_2}{w \times r \times a_1} \quad (5)$$

Table 3 Group Distribution.

Group Number	Composition Type	Dominant Group (70%)	Auxiliary Group (20%)	Marginal Group (10%)
F1	Comprehensive Area	average	average	average
F2	Young Adult Dominated Area	g1、g5(40%) g2、g6(30%)	g3、g7	g4、g8
F3	Parent-Child Dominated Area	g3、g7	g1、g5、g2、g6	g4、g8
F4	Elderly Dominated Area	g4、g8	g1、g2、g5、g6	g3、g7

Based on the allocated experimental groups, the changes in evacuation times across different densities and group-dominant areas are analyzed, as shown in Fig. 6. Evacuation times in all areas show a monotonically increasing trend with rising population density, with low-density increases being gradual and high-density increases being sharp. When density is below 0.4 persons/m², the time increase in each area is small; however, when density exceeds 0.6 persons/m², the increase becomes significantly larger. For example, the elderly-dominant area (F4) shows a 52.2% increase, where space becomes the primary limiting factor affecting evacuation efficiency. Additionally, evacuation efficiency across areas shows consistent differences at the same density, with the young adult-dominant area (F2) > the comprehensive area (F1) > the parent-child-dominant area (F3) > the elderly-dominant area (F4). As density increases, these differences become more significant, highlighting the amplified efficiency disadvantage of slower groups at higher densities. Furthermore, areas dominated by vulnerable groups exhibit much greater sensitivity to increasing density compared to the young adult-dominant area. The total increase in evacuation time follows the order: F4 (52.2%) > F3 (37.6%) > F1 (25.8%) > F2 (24.8%). This is because, in high-density environments, the slow speed characteristics of the elderly and the behavioral dependency of children more easily lead to global congestion. Moreover, the density range between 0.4 persons/m² and 0.6 persons/m² represents a critical transition point for evacuation efficiency. Within this range, the increase in evacuation time across areas sharply rises, marking the shift from sufficient to constrained space.

With a fixed population density of 0.8 persons/m² and a total of 480 individuals, the relationship between the proportions of young adults, children, and elderly individuals and evacuation times is analyzed, as shown in Fig. 7. When the proportion of young adults is low, their speed advantage is more pronounced, leading to stronger competitiveness. As the proportion of young adults increases, evacuation time decreases. However, when the proportion exceeds 70%, overall evacuation time begins to rise. This is due to the

concentration of young adults at bottlenecks such as exits, causing congestion as they compete for limited space, resulting in a mismatch between speed advantage and spatial competition. Even though young adults move faster, the waiting time at exits exceeds the time saved in non-conflicting areas, resulting in a "faster is slower" phenomenon [36]. As the proportion of slow-moving groups, such as children and elderly, increases, evacuation time increases as well, with a decreasing rate of increase. This is due to the fact that when slow-moving groups are in the minority, the leading ability of the faster groups compensates for their speed disadvantage. However, as slow-moving groups become the majority, the guiding capacity of the young and healthy individuals exceeds a critical threshold, and the combined effects of speed disadvantages and spatial competition lead to global congestion, causing a rapid increase in evacuation time. Once the slow-moving groups dominate the evacuation, homogeneity within the group increases, and efficiency becomes constrained by the group's speed and the exit capacity, resulting in a slower and more stabilized increase in evacuation time.

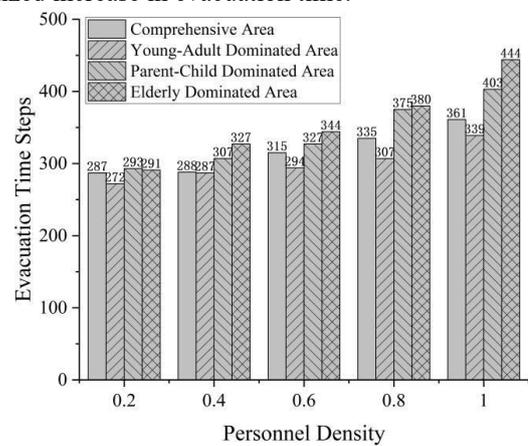


Fig. 6. Evacuation Time Variation in Group-dominated Areas

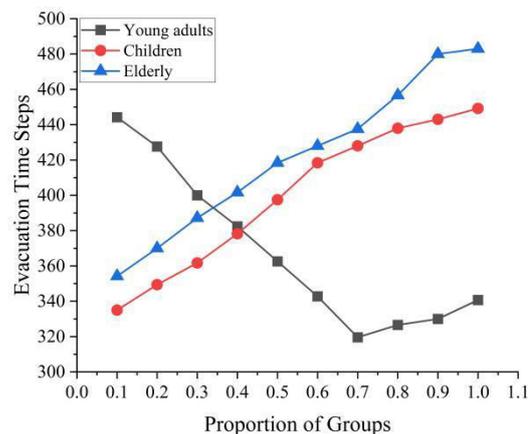


Fig. 7. Relationship between the of Groups and Evacuation Time

B. Comparison of Conflict Resolution Strategies

With the proportion of independent individuals fixed at 20%, the optimization effects of two conflict resolution strategies under different pedestrian densities were simulated, as shown in Fig. 8. In the density range of 0.1~1.0 persons/m², the evacuation times for both strategies show a trend of convergence at low densities and divergence at high densities, both rising slowly with increasing density. In low-density intervals, where spatial resources are sufficient,

the frequency of conflicts between groups competing for the same cell is minimal, and the evacuation times for both strategies are similar. However, when the density exceeds 0.5 persons/m², spatial competition intensifies, and Strategy 2 shows a clear advantage. Strategy 1 allows a large number of fast-moving groups to reach the exit first, which can easily lead to congestion at evacuation bottlenecks. Vulnerable groups are continuously blocked and accumulate at the rear, forming moving obstacles that impede the progress of faster groups, causing the time saved by the fast groups to be offset by congestion time, ultimately reducing evacuation efficiency. Strategy 2, by prioritizing the passage of vulnerable groups, effectively maintains smooth flow in the evacuation path, significantly improving overall evacuation efficiency. This trend indicates that at a density of 0.5 persons/m², the choice of strategy has little impact in low and medium-density scenarios, but in high-density environments, prioritizing vulnerable groups can significantly alleviate congestion.

At a density of 0.8 persons/m², the evacuation states at time steps 100 and 200 for both strategies are shown in Fig. 9. It can be seen that under Strategy 1, a large number of fast-moving groups, represented by blue, reach the exit first, leading to congestion at the exit. In contrast, Strategy 2 maintains overall stability in the evacuation process, further confirming that prioritizing vulnerable groups at high densities enhances evacuation efficiency.

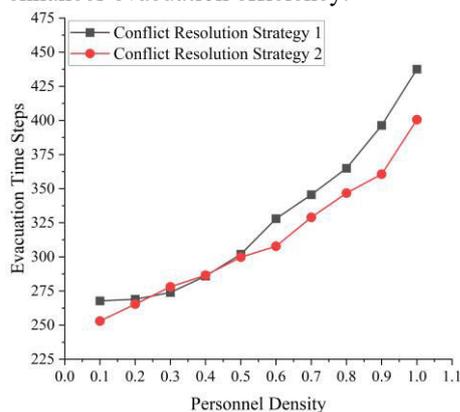


Fig. 8. Relationship between Conflict Resolution Strategies and Evacuation Time

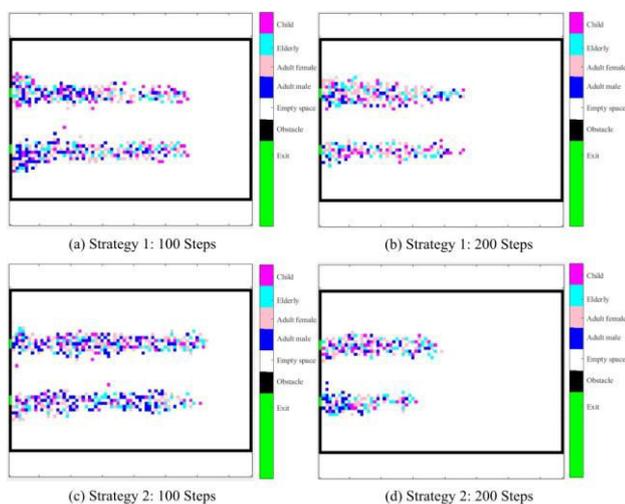


Fig. 9. Schematic of Conflict Resolution Strategies in the Cellular Automaton

C. Analysis of the Impact of Environmental Familiarity on Evacuation

Environmental familiarity was set from 0.1 to 1, with visibility (R) fixed at 5. Pedestrians in unfamiliar environments followed a flocking evacuation strategy. The impact of environmental familiarity on evacuation time at densities of 0.2, 0.4, 0.6, 0.8, and 1.0 was studied, as shown in Fig. 10. At a constant density, environmental familiarity is negatively correlated with evacuation time, and increasing environmental familiarity significantly shortens evacuation time, improving evacuation efficiency, with a maximum reduction of 36.9%. Meanwhile, evacuation time is significantly positively correlated with pedestrian density. As the density increases from 0.2 to 1.0 persons/m², evacuation time increases systematically across all levels of environmental familiarity, with the highest increase reaching 59.2%.

Furthermore, the study found a significant interaction effect between the two independent variables, with the impact of environmental familiarity on evacuation efficiency being more pronounced in low-density environments. This effect gradually diminishes as pedestrian density increases. This suggests that under high-density conditions, physical constraints such as reduced mobility efficiency and increased path conflicts due to crowding have become the dominant factors limiting evacuation efficiency, thereby partially weakening the advantages of environmental familiarity in decision-making and path optimization.

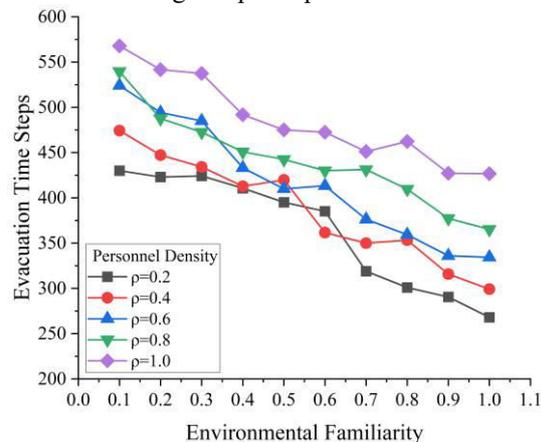


Fig. 10. Relationship between Environmental

D. Analysis of the Impact of Visibility on Evacuation

With environmental familiarity fixed at 0.5, the impact of fire visibility on evacuation time was analyzed under varying pedestrian densities. The visibility (R) was set at 5, 7, 9, 11, 13, and 15, as shown in Fig. 11. The results reveal significant differences in how visibility influences the evacuation process under different pedestrian densities. In a low-density environment (0.2 persons/m²), where spatial resources are relatively abundant and there is minimal competition between individuals, increasing visibility optimizes path recognition efficiency. This helps individuals quickly locate exits, reducing hesitation and stagnation. The optimal evacuation time is achieved at $R=15$, which is 15.2% shorter than at $R=5$. At medium densities (0.4~0.6 persons/m²), evacuation efficiency is highest when $R=5$. Although higher visibility improves individuals' ability to recognize exits and paths, allowing more pedestrians to quickly perceive and

choose optimal routes, the concentration of information may cause a large number of individuals to flock to the same exit or narrow passage. This increases spatial competition and congestion. In contrast, in low-visibility environments, pedestrians, due to limited perception, tend to move more randomly, which can, to some extent, reduce excessive crowding at a single passage. Therefore, in medium-density scenarios, high visibility does not always shorten evacuation time. Over-concentration of choices may lead to bottlenecks in local areas, delaying the overall evacuation process. In high-density environments (0.8~1.0 persons/m²), where spatial resources are highly constrained, the impact of visibility diminishes significantly. The fluctuation in evacuation time is only 12% across different visibility levels. Spatial competition becomes the primary issue, and pedestrian movement is restricted by congestion, diminishing the advantage of visibility. For the same visibility level, evacuation time increases with density. In low-density stages, the increase is gradual, while in medium to high densities (above 0.6 persons/m²), congestion intensifies, and evacuation time continues to increase, with a significantly larger rate of increase.

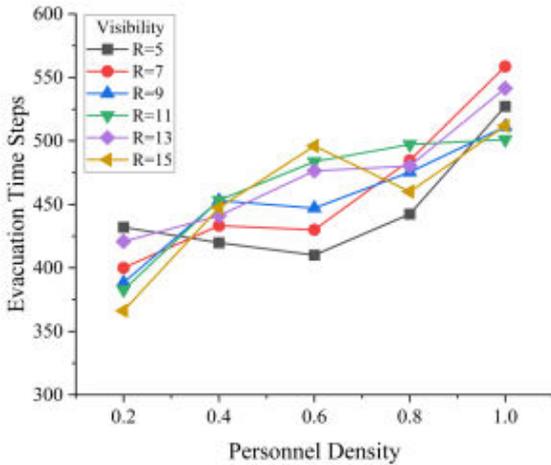


Fig. 11. Relationship between Visibility and Evacuation Time

E. Parameter Sensitivity Analysis

To verify the reliability of the physical energy consumption and recovery mechanisms and the rationality of parameter values in the model, sensitivity analysis was conducted on key parameters. The simulation was set at a density of 0.6 persons/m², with all individuals being familiar with the environment. Each simulation scenario contained only one type of individual. Sensitivity tests were conducted for the energy consumption rate (a_1), energy recovery rate (a_2), energy threshold (w), and recovery upper limit (r) for four types of individuals, with total evacuation time as the indicator. The results are shown in Fig. 12.

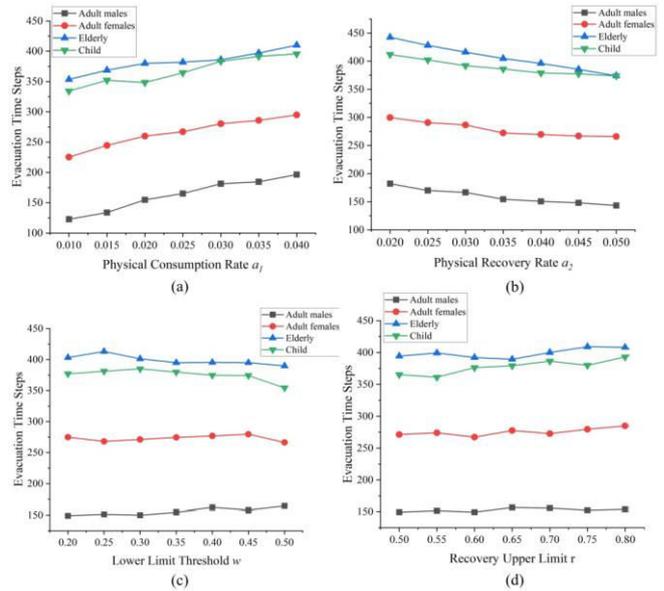


Fig. 12. Sensitivity Variations of a_1 、 a_2 、 w 、 r

The results indicate that the model is highly sensitive to the energy consumption and recovery rates, with the sensitivity gradient aligning with the physical characteristics of the populations. Adult males are most sensitive to changes in a_1 , with an increase in evacuation time by 60%, reflecting that groups with higher base speeds are more susceptible to energy consumption increases. The elderly group's evacuation time significantly decreases with an increase in a_2 , with a time reduction of 15%, indicating that the elderly, who have the weakest physical foundation and slowest recovery, experience the greatest marginal benefit from improving recovery efficiency. The differentiated responses of different groups to the same physiological mechanisms strongly support the setting of differentiated parameter values for the four types of individuals, which is not only reasonable but also essential for accurate modeling. This ensures that the model can capture the core physiological differences of heterogeneous populations during evacuation.

Regarding the physical threshold parameters, the model shows no regular response to changes in the energy depletion threshold (w) or recovery threshold (r), indicating that these parameters are secondary in the current scenario. This suggests that in medium-density environments, pedestrian movement is primarily constrained by available space, and small shifts in energy states have limited impact on the overall evacuation process. Therefore, the threshold parameters set in this study based on the literature have good robustness within this framework and can serve as reliable default values without requiring extensive calibration.

This study reveals the differences in sensitivity between groups, which in turn validates the rationale behind the differentiated parameter settings. This ensures that all conclusions drawn from the complex simulations involving companion behavior are based on a heterogeneous population model that accurately and reliably responds to physiological mechanisms.

IV. CONCLUSION

This study systematically reveals the interaction mechanisms between companion behavior and heterogeneous populations in the fire evacuation of

commercial complexes by constructing a multi-factor cellular automaton model. The main conclusions are summarized as follows:

- 1) The composition and size of groups are key factors determining evacuation efficiency. Groups led by young adults are the most efficient, while groups with a high proportion of elderly and children are more prone to persistent congestion. Independent individuals, due to their flexibility, can effectively aid in flow organization and optimize traffic flow in high-density environments.
- 2) Personnel density is the dominant parameter. When the density exceeds 0.6 persons/m², spatial competition becomes the main issue, replacing other factors. Both environmental familiarity and visibility exhibit strong density dependence: the former shows a clear advantage at low densities, while the latter may have negative effects at medium densities due to increased path competition.
- 3) Conflict resolution strategies should be selected based on the density conditions. In high-density environments, adopting a vulnerable group priority strategy rather than a fast group priority strategy is more effective at preventing exit congestion, thereby enhancing overall evacuation efficiency.

The simulation results of this study provide significant insights for emergency evacuation planning in commercial complexes. Managers should focus on the demographic characteristics of each area, implement appropriate guidance strategies in high-density regions, and recognize the importance of environmental familiarity in the early stages of evacuation.

This study has certain limitations: the model is based on a relatively simple 2D space, and future work could extend it to more complex multi-story commercial complex structures. Additionally, social interaction mechanisms such as psychological dependence and communication waiting within companion behavior have not been fully modeled. Future research could incorporate surveys and video data mining to further refine behavioral rules and use real evacuation cases for model validation and calibration.

REFERENCES

- [1] A. Varas, M.D. Cornejo, D. Mainemer, B. Toledo, J. Rogan, V. Muñoz, J.A. Valdivia, Cellular automaton model for evacuation process with obstacles, *Physica A: Statistical Mechanics and its Applications* 382 (2007) 631-642.
- [2] S. Xing, C. Wang, W. Wang, R.F. Cao, A.C.Y. Yuen, E.W.M. Lee, G.H. Yeoh, Q.N. Chan, A fine discrete floor field cellular automaton model with natural step length for pedestrian dynamics, *Simulation Modelling Practice and Theory* 130 (2024) 102841.
- [3] X. Xiong, L. Luo, Y. Feng, Z. Fu, J. Ma, Development of floor field cellular automaton model for pedestrian dynamics: Incorporating empirical acceleration mechanisms, *Simulation Modelling Practice and Theory* 144 (2025) 103197.
- [4] Y. Song, Z. Yu, F. Huo, L. Wei, Y. Ma, Study on evacuation cellular automaton model considering avoidance behavior, *Journal of System Simulation* 32 (2020) 975-981.
- [5] X. Xu, C. Shi, J. Li, H. Che, Study on cellular automata model of personnel evacuation considering detour effect, *Journal of Safety Science and Technology* 14 (2018) 20-25.
- [6] C. Chen, T. Lu, An extended model for crowded evacuation considering stampede on inclined staircases, *Simulation Modelling Practice and Theory* 135 (2024) 102978.
- [7] C. Chen, N. Wang, B. Xi, Research on evacuation cellular automata model of evacuees with luggage, *China Safety Science Journal* 24 (2014) 3-9.
- [8] Z. Shang, J. Zhang, Z. Shi, X. Li, W. Song, Enhancing evacuation efficiency: Investigating how luggage influences exit strategies and crowd dynamics, *Simulation Modelling Practice and Theory* 142 (2025) 103142.
- [9] L. Chen, T.-Q. Tang, Z. Song, H.-J. Huang, R.-Y. Guo, Child behavior during evacuation under non-emergency situations: Experimental and simulation results, *Simulation Modelling Practice and Theory* 90 (2019) 31-44.
- [10] Y. Li, C. Lu, J. Jin, Simulation of a pediatric hospital in evacuation considering groups, *Simulation Modelling Practice and Theory* 107 (2021) 102150.
- [11] B. Zou, C. Lu, Y. Li, Simulation of a hospital evacuation including wheelchairs based on modified cellular automata, *Simulation Modelling Practice and Theory* 99 (2020) 102018.
- [12] H. Feizhou, F. Dandan, L. Chang, M. Yaping, L. Zihan, L. Mengling, Study on evacuation model considering companion behavior and emotion contagion, *China Safety Science Journal* 33 (2023) 126.
- [13] M. Shi, E.W.M. Lee, Y. Ma, A dynamic impatience-determined cellular automata model for evacuation dynamics, *Simulation Modelling Practice and Theory* 94 (2019) 367-378.
- [14] C. Lu, W. Weng, R. Yang, Fire evacuation model based on motor schema and cellular automaton, *JOURNAL-TSINGHUA UNIVERSITY* 47 (2007) 2163.
- [15] C. Chen, R. Yu, S. Wang, Q. Dai, Modelling of crowd evacuation behavior considering the effects of drunken gait, *Simulation Modelling Practice and Theory* 142 (2025) 103128. <https://doi.org/10.1016/j.simpat.2025.103128>
- [16] J. Huang, X. Liu, Y. Ji, F. Song, T. Jiang, T. Du, X. Fan, An improved CA model for evacuation simulation in super high-rise buildings: Considering evacuees' rest on refuge floors and preference for taking evacuation elevators, *Simulation Modelling Practice and Theory* 143 (2025) 103148.
- [17] G. Qi, W. Weili, Experimental study on pedestrian evacuation considering small group behavior, *China Safety Science Journal* 31 (2021) 172.
- [18] K. Zhu, Y. Yang, Q. Shi, Study on evacuation of pedestrians from a room with multi-obstacles considering the effect of aisles, *Simulation Modelling Practice and Theory* 69 (2016) 31-42.
- [19] C.-Y. Li, R.-Y. Yang, L. Chen, T.-Q. Tang, A boarding model for heterogeneous passengers on the platform of high-speed railway station, *Simulation Modelling Practice and Theory* 106 (2021) 102188.
- [20] Z. Rui, Y. Jing, Y. Chenwei, Pedestrian simulation modeling of subway corridor considering group behavior, *Journal of Transportation Systems Engineering and Information Technology* 19 (2019) 163-168.
- [21] J. Neto, A.J. Morais, R. Gonçalves, A.L. Coelho, Guiding Evacuees to Improve Fire Building Evacuation Efficiency: Hazard and Congestion Models to Support Decision Making by a Context-Aware Recommender System, *Buildings* 13 (2023) 3038.
- [22] M. Moussaïd, D. Helbing, G. Theraulaz, How simple rules determine pedestrian behavior and crowd disasters, *Proceedings of the National Academy of Sciences* 108 (2011) 6884-6888.
- [23] R. Rastogi, I. Thaniarasu, S. Chandra, Design Implications of Walking Speed for Pedestrian Facilities, *Journal of Transportation Engineering* 137 (2011) 687-696.
- [24] F. Qiu, X. Hu, Modeling group structures in pedestrian crowd simulation, *Simulation Modelling Practice and Theory* 18 (2010) 190-205. <https://doi.org/10.1016/j.simpat.2009.10.005>
- [25] S. Yinghua, T. Wenhao, H. Feizhou, Study on cellular automata model of pedestrian evacuation considering environmental familiarity and guidance, *Journal of Safety Science and Technology* 16 (2020) 56-60.
- [26] Y. Mao, Z. Fan, J. Zhao, Q. Zhang, W. He, An emotional contagion based simulation for emergency evacuation peer behavior decision, *Simulation Modelling Practice and Theory* 96 (2019) 101936.
- [27] L. Chen, Z.-L. Guo, Y.-X. Li, J. Zhang, T.-Q. Tang, Y.-Y. Chen, Research on pedestrian evacuation considering group behavior under zero-visibility condition, *ACTA PHYSICA SINICA* 73 (2024).
- [28] R.L. Knoblauch, M.T. Pietrucha, M. Nitzburg, Field Studies of Pedestrian Walking Speed and Start-Up Time, *Transportation Research Record* 1538 (1996) 27-38.
- [29] L. Quanping, L. Jiahong, L. Meng, Study on Crowd Evacuation Behaviors Based on Multi-Agent and Cellular Automata Technology, *Computer simulation* 31 (2014) 328-332.
- [30] N. Ding, T. Chen, H. Zhang, Simulation of high-rise building evacuation considering fatigue factor based on cellular automata: A case study in China, *Building Simulation* 10 (2017) 407-418.
- [31] S. Das Gupta, M.F. Bobbert, D.A. Kistemaker, The Metabolic Cost of Walking in healthy young and older adults – A Systematic Review and Meta Analysis, *Scientific Reports* 9 (2019) 9956.

- [32] S. Zanconato, D. Cooper, Y. Armon, Oxygen cost and oxygen uptake dynamics and recovery with 1 min of exercise in children and adults, *Journal of Applied Physiology* 71 (1991) 993-998.
- [33] F. Xu, E.C. Rhodes, Oxygen Uptake Kinetics During Exercise, *Sports Medicine* 27 (1999) 313-327.
- [34] Z. Ze-tian, L. Yi-xue, Q. Kai-bo, M. Zhan-li, Research on small group evacuation time based on agent model, *Fire Science and Technology* 39 (2020) 305.
- [35] E. Ronchi, D. Nilsson, Fire evacuation in high-rise buildings: a review of human behaviour and modelling research, *Fire Science Reviews* 2 (2013) 7.
- [36] D. Helbing, I. Farkas, T. Vicsek, Simulating dynamical features of escape panic, *Nature* 407 (2000) 487-490.

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