



Impact of the caregiver-to-resident ratio on evacuation efficiency in nursing homes: A simulation-based study

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ABSTRACT

With the growing aging population, ensuring effective and safe evacuation of older people in nursing homes has become a pressing concern in emergency planning. This study presents an enhanced agent-based evacuation model that explicitly incorporates caregiver-assisted movement dynamics, intelligent pathfinding, and collision avoidance to simulate evacuation processes in nursing homes. The model is applied to evaluate the caregiver-to-resident ratio's influence on the evacuation efficiency of residents with different distributions. The results demonstrate that increasing the caregiver-to-resident ratio does not positively affect evacuation efficiency and may even hinder it in complex building layouts. When caregivers are rationally allocated, evacuation time in scenarios involving wheelchair users can be shorter than in those without wheelchairs, due to more coordinated and assisted movements. These findings provide valuable insights for optimizing the evacuation strategies of nursing homes and emphasize that the allocation of caregivers needs to consider the locations of residents and their mobility capabilities.

1. Introduction

As aging societies have emerged, the safety of older residents in nursing homes, especially during emergencies like fires, has become increasingly important. Traditional building designs may not account for the physical and cognitive limitations of the older people, complicating evacuations and increasing risks. Thus, developing effective evacuation strategies is a critical challenge.

Considering the growing aging population and the increasing demand for nursing homes, the government, building designers as well as researchers have paid great concern on the safety of older people, in particular their evacuation characteristics in case of emergency. Egress data reflecting the evacuation behaviors of heterogeneous pedestrians have been collected and analyzed [1,2]. Aged pedestrians exhibit self-organizing phenomena similar to younger individuals but with lower flow rates [3], suggesting the need for wider exits [4]. Slow walking speeds in mixed-age evacuation crowds significantly reduce overall flow rates [5,6], and older pedestrians walk much slower than young adults [7,8]. The presence of older people in mixed-age groups alters the motion dynamics and evacuation efficiency [9], with younger assistants prioritizing older people's movement [10]. Observations from fire drills in Canadian nursing homes show 72 % of residents require full assistance, emphasizing staff's critical role [11]. The participation rate of the target population in local evacuation drills improved following their involvement in indoor evacuation drills [12]. Fire drills in nursing homes highlight the need for optimal staffing levels and doubt the assumption that more staff members always lead to better outcomes [13]. A systematic review emphasizes staff responsiveness and training [14]. These findings highlight the need for tailored

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evacuation strategies for older people.

Besides the empirical studies, many simulation models have been developed to investigate the movement characteristics of older people. Table A1 summarizes the key features and limitations of these simulation-based studies. Cellular automata (CA) methods have been applied to simulate assisted fire evacuation in nursing homes, analyzing behavioral characteristics [15,16], showing that placing non-self-evacuating patients on lower floors [17], optimal avoidance by vulnerable individuals [18] and separating lanes for slow and normal-speed walkers [19] help safe evacuation. However, due to the discrete nature of time and space in CA models, they often cannot fully capture the complexity of continuous individual behaviors, interactions, and dynamic responses during evacuations (e.g. the dynamic assistance processes between caregivers and residents) and simplify to rule-based state transitions within fixed cells. This limitation hinders the accurate representation of coordinated, reverse-flow, and adaptive decision-making in real-world emergencies.

Agent-based models have been proposed as a more flexible alternative, allowing continuous representation of space and time and detailed modeling of individual behaviors and interactions. An evaluation of building egress safety for older people using an agent-based model has been proposed, incorporating absolute and relative indicators [20]. Agent-based models incorporated detailed behaviors of evacuees and rescuers have been widely applied in evacuations, allowing for the evaluation of optimal rescue plans and strategies [21], showing that assigning older occupants to caregivers according to their zones and evacuating them together reduces the evacuation time [22], finding that prioritizing the assistance of disabled older people followed by aiding the nearest disabled individuals reduces evacuation time, while a spatial layout with disabled rooms concentrated in the center enhances evacuation efficiency [23], enabling older or disabled individuals to evacuate autonomously and minimizing the need for healthcare staff assistance [24], evaluating planned environment and identifying ways to make the environment more age-friendly [25], indicating that increasing the ratio of assisting caregivers improves evacuation efficiency for stair evacuations [26]. Software like NetLogo, AnyLogic, Pathfinder, and MassMotion further illustrate the benefits of agent-based approaches, demonstrating enhanced evacuation efficiency through dedicated exits, elevators, and strategic placement of older individuals [27–33].

Based on existing literature, the evacuation of older people faces high difficulties due to their reduced mobility and cognitive abilities. Caregiver assistance and evacuation route design significantly impact evacuation efficiency. Considering that structural modifications to existing buildings are often impractical, caregiver support becomes a key factor in reducing evacuation time. Therefore, studying the influence of caregivers is important for ensuring the safety of older individuals and enhancing society's emergency response capabilities. However, a key question remains: does increasing the caregiver-to-resident ratio always lead to faster evacuations, especially when residents have different mobility, such as wheelchair users? In practice, caregivers often move against the flow of evacuees to reach residents requiring assistance. This counter-flow movement can create congestion and potentially delay the overall evacuation process. As a result, the assumption that more caregivers always result in quicker evacuations needs further investigation.

To address this question, this study introduces an enhanced agent-based model to simulate caregiver-assisted evacuations in nursing homes. Simulations are conducted in a real-world complex nursing home. The study investigates the influence of two key factors: *the caregiver-to-resident ratio* ($r = 0.2, 0.4, 0.6, 0.8, 1.0$) and *the presence of wheelchair users (with or without)* on evacuation efficiency. Only wheelchair users and residents with full mobility are considered in this study and bedridden older people who require high-level care are not taken into account. The goal of this research is to provide actionable insights for optimizing evacuation strategies in nursing homes and improving emergency response capabilities.

In the following sections, Section 2 introduces the proposed agent-based model. Section 3 presents the simulation scenarios and the simulated results. Section 4 provides a detailed discussion of the findings obtained from the simulations. Finally, Section 5 summarizes this study.

2. Model development: CityFlow-N

2.1. Original CityFlow model

The original CityFlow [34] model consists of two key modules: a strategic navigation module for long-term route planning toward exits, and an operational movement module for short-term behaviors like collision avoidance and speed adjustment. The strategic module determines temporary regional targets for each pedestrian based on their route choice, while the operational module decides local movement at every time step.

Pedestrians are represented as circular agents with 0.4 m diameter, and a forward-facing view defined by a radius $R = 3$ m and an angle $\theta = 170^\circ$. Possible movement directions within the view range are discretized into N directions, with an angular interval $\Delta\theta = \theta/N$. At each time step, an agent evaluates the utility U_k of each direction k and selects the optimal one:

$$U_k = \omega_e E_k + \omega_o O_k + \omega_p P_k + \omega_a A_k + \omega_i I_k + \xi$$

where E_k represents movement efficiency toward the target, O_k denotes obstacle avoidance, P_k and A_k capture interactions with other pedestrians, I_k reflects inertia, and ξ is a stochastic term. The agent then moves one step according to the selected direction. Its speed $v_{i,t}$

is determined by the local density using Weidmann's empirical formula $v_{i,t} = v_f \times \left\{ 1 - e^{\left[-\gamma \left(\frac{1}{\rho_t} - \frac{1}{\rho_{\max}} \right) \right]} \right\}$, where v_f is the free moving speed, ρ_t is the local density within the view range, $\rho_{\max} = 5.4 \text{ m}^{-2}$, and $\gamma = 1.913$ [35].

2.2. Model framework and enhancements

While the original model effectively simulates pedestrian behavior [34,36], we extend it for caregiver-assisted evacuations in nursing homes by introducing a rescue assistance module, forming the enhanced CityFlow-N model. This module governs the behavior of rescuers, who actively search for individuals requiring help (e.g., wheelchair users or older people) and guide them toward exits. As illustrated in Fig. 1, the rescue module interacts with the strategic navigation module by updating regional targets when agents requiring assistance are detected. This extension enables rescuers to balance exploration (searching for individuals in need) and assistance (guiding assisted agents to exits).

Rescuers have a limited visual perception defined as a sector with a radius of 3 m [34] and an angular span of 120° [37,38]. This defines the search range within which rescuers can detect agents needing assistance, as shown in Fig. 2. An agent is detected if its Euclidean distance d from the rescuer satisfies $d \leq R$, and the relative angle between the rescuer’s facing direction and the agent’s position is less than $\theta/2$. These detection parameters are consistent with prior agent-based evacuation models [34,37], ensuring realistic detection and interaction distances.

The proposed rescue assistance module is critical for modeling the dynamic role of rescuers during evacuations. Rescuers actively search for agents in need, such as those with mobility impairments or wheelchair users, and provide assistance by guiding them to exits. Given the limited number of rescuers, the module introduces a tiered logic for selecting who to assist: (1) Search Phase. Rescuers scan their current region for agents in need. If no individuals are detected, the search expands sequentially to neighboring regions based on the predefined network connection order. (2) Selection Phase. The rescuer selects the nearest agent needing help, prioritizing wheelchair users. If multiple candidates are detected, the closest individual is selected. If two caregivers detect the same resident and the distances are equal, one caregiver is randomly selected to assist the agent. (3) Assistance Phase. Once an agent is located, the rescuer guides the agent toward the exit. Both rescuer and agent move together with synchronized velocities.

After completing a rescue and reaching the exit, the rescuer does not return to the initial position. Instead, the rescuer begins the next search from their current location. As shown in Fig. 3, following the region-based search logic, the rescuer first scans the region adjacent to the exit (Region 6). If no unassisted agents are detected, the rescuer continues the search into neighboring regions (Region 4), following the predefined region connection order.

The environment is modelled using a network-based approach [34], as shown in Fig. 3. The environment is divided into “regions” interconnected by “edges”. Every region is defined within a 2D continuous space, bounded by geometric constraints, while the edges define the connections between regions. In Fig. 3, a rescuer is positioned in Region 1 and systematically searches adjacent regions to identify individuals in need of assistance. An agent in need is shown in orange within Region 3. Upon locating the orange agent, the rescuer provides assistance and guides the agent toward the exit together. The flow chart of the evacuation process is shown in Fig. 4.

2.3. The rescuer-assisted agent interaction

The interaction process between a rescuer (caregiver) and the assisted agent (wheelchair user or older person) follows a dynamic process of matching, binding and coupling. The agents in the simulation are divided into three sets: S (set of rescuers), E (set of older residents), and W (set of wheelchair users). The set of agents requiring assistance is $A = E \cup W$. Each agent i is characterized by a state vector at time t , denoted as $\mathbf{X}_i(t) = \{\mathbf{x}_i(t), \mathbf{v}_i(t), dv_i(t), \theta_i(t), r_i(t), \mathbf{c}_i(t), h_i(t)\}$, where $\mathbf{x}_i(t)$ represents the 2D position, $\mathbf{v}_i(t)$ the velocity, $dv_i(t)$ the desired speed, $\theta_i(t)$ the movement direction, $r_i(t)$ the current region, $\mathbf{c}_i(t)$ the surrounding perception, and $h_i(t) \in \{-1, j\}$ the help-link identifier.

A rescuer $s \in S$ can perceive potential assisted agents within the same region. The set of candidates $C(s, t) = \{a \in A \mid h_a(t) = -1, r_a(t) = r_s(t)\}$ includes agents within the same region and not yet linked to another rescuer. The rescuer selects the closest agent from this set, with wheelchair users prioritized. To prioritize wheelchair users, a priority-adjusted distance $d'(s, a)$ is defined as $d'(s, a) = \{d(s, a) - \Delta w, \text{ if } a \in W, \Delta w > 0\}$. The rescuer selects the assistance target a^* as the candidate with the minimum priority-adjusted distance $a^*(s, t) =$

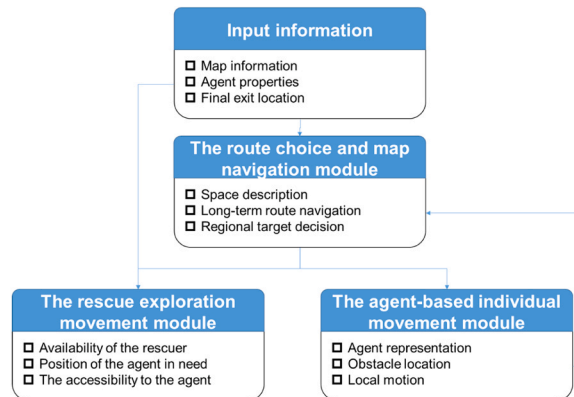


Fig. 1. Framework of the enhanced CityFlow-N model.

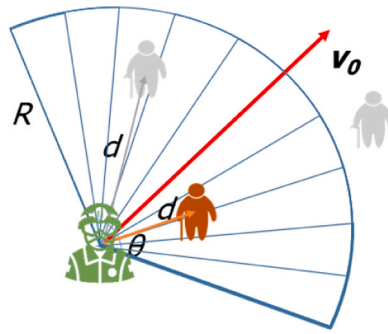


Fig. 2. Illustration of rescuer searching for an agent in need. R represents the field-of-view radius and θ represents the angle of field of view. v_0 represents the desired velocity of the rescuer. d represents the Euclidean distance between the rescuer and the agent in need. Once the rescuer identifies the nearest agent requiring assistance, the rescuer approaches the agent to offer help. Noted that agents outside of the visual field are not detected.

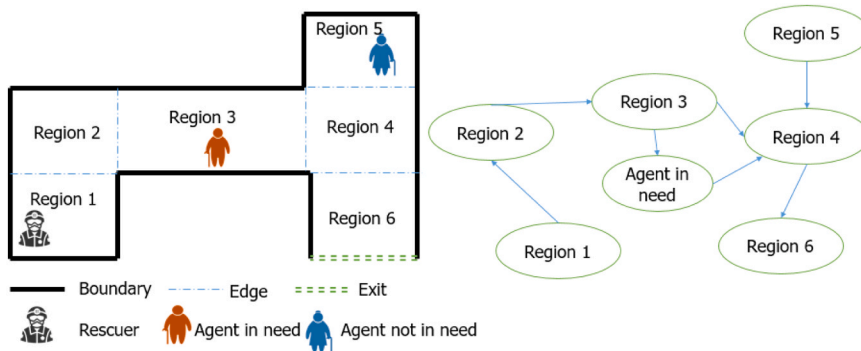


Fig. 3. Space representation of the simulation environment, illustrating regions, edges, exits and agent roles (rescuer in Region 1, agent in need in Region 3, agent not in need in Region 5).

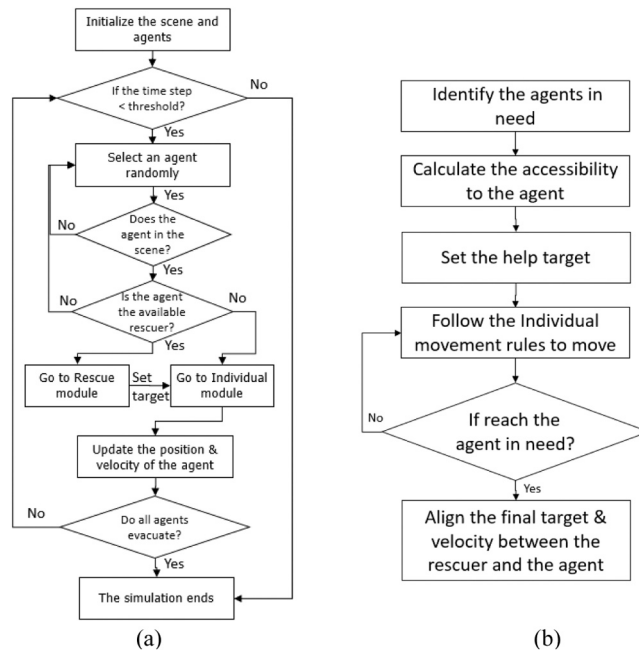


Fig. 4. Flow chart of pedestrian's movement process in the building. (a) The overall evacuation workflow. (b) The rescue assistance sub-process.

$\arg \min_{a \in C(s,t)} d'(s,a)$. Once selected, a help-link is established by setting $h_s(t) = \text{ID of } a^*$. Assistance becomes active when the rescuer moves within a critical assistance radius R_s of the target agent, i.e., $d(s,a^*) \leq R_s$. At this point, both the rescuer and the assisted agent synchronize their speeds and directions, moving together as a coordinated unit. Both agents follow the same behavioral pipeline of the CityFlow model, sharing the same target, speed, and direction. This ensures their positions remain closely coupled $|\mathbf{x}_s(t+1) - \mathbf{x}_{a^*}(t+1)| \approx \text{constant}$. The assistance link is terminated if the rescuer and the assisted agent become spatially separated, such as when the assisted agent reaches the exit. Upon termination, the rescuer then re-enters the search phase to identify the next agent in need.

2.4. Model credibility

To verify the credibility of the proposed CityFlow-N model, a bottleneck evacuation simulation is conducted, and the results are compared with empirical data. The simulated scenario closely follows the setup from the empirical study [10]. To be consistent with the experimental setup, initially, 30 older agents (expected walking speed: 1.28 m/s) and 60 caregiver agents (expected walking speed: 1.4 m/s) are randomly distributed in the waiting area and gradually move through the bottleneck. All older agents receive assistance from the caregivers. The bottleneck width b is varied from 1.0 m to 1.6 m in intervals of 0.2 m, as shown in Fig. 5. Each condition is repeated 10 times to enrich the data (Fig. 6).

The evacuation time obtained from the simulation is compared with corresponding experimental measurements. As shown in Table B1 (in Appendix B), the experimental results fall within the 95 % confidence interval (CI) of the simulated means for bottleneck widths of 1.0, 1.2, and 1.4 m, indicating a statistically significant agreement. For the 1.6 m bottleneck, the experimental value lies outside the 95 % CI but remains within the $\pm 2\sigma$ range of the simulation distribution, suggesting a reasonable yet slightly weaker correspondence. Overall, the model demonstrates a robust capability to reproduce experimental evacuation time across varying bottleneck widths.

3. Simulation scenarios and results

This study simulates a nursing home evacuation scenario to investigate the impact of caregiver assistance on evacuation efficiency. Section 3.1 describes the simulation setup. Section 3.2 and Section 3.3 compare the evacuation time and individual speed in different conditions, respectively.

3.1. Scenario setup

The simulated nursing home represents a real-world facility in Hong Kong, consisting of several small rooms and three exits: one 2 m wide exit and two 1.5 m wide exits, as shown in Fig. 7. The building is discretized into small regions and the evacuation route is shown in Fig. 8. Agents in the building move from their respective regions to the nearest exit, following the designed evacuation route.

Fig. 9 shows the simulated three scenarios: (1) no wheelchair users, (2) wheelchair users with initial positions near the exit, and (3) wheelchair users with initial positions far from the exit. The study aims to investigate the impact of the caregiver-to-resident ratio on evacuation efficiency under these three conditions. In the simulation, 100 older agents and varying numbers of caregivers (20, 40, 60, 80, 100) are randomly distributed across different rooms.

The agents are represented as circles, with diameters of 0.38 m for older residents, 0.39 m for caregivers, and 0.80 m for wheelchair users [39,40]. The expected walking speeds of older people follows a Gaussian distribution with a mean of 1.0 m/s and a standard deviation of 0.2 m/s [30,41]. Caregivers have an expected moving speed of 4.0 m/s [42]. When assisting an older resident, the combined speed of the caregiver and the older person is fixed at 1.4 m/s, as stated in [10]. Wheelchair users are unable to move independently and when assisted by the caregivers, their combined expected speed is 2.72 m/s, following previous empirical data [43].

3.2. Evacuation time

The evacuation time is defined as the duration from the start of the evacuation until the last person leaves the nursing home. Fig. 10

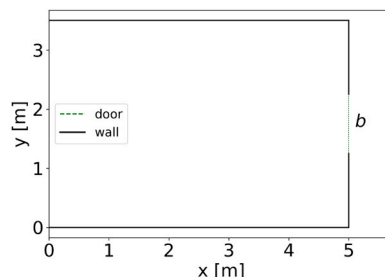


Fig. 5. Simulated bottleneck scenario with adjustable width b . b varies from 1.0 m to 1.6 m at the interval of 0.2 m.

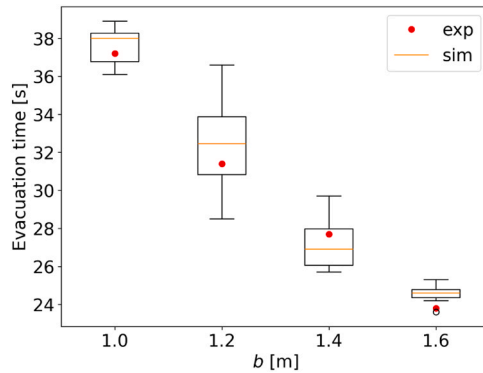


Fig. 6. Comparison of the relation between evacuation time and bottleneck width b between the experimental and simulation results. Simulated results (boxes) closely match experimental data (red points).

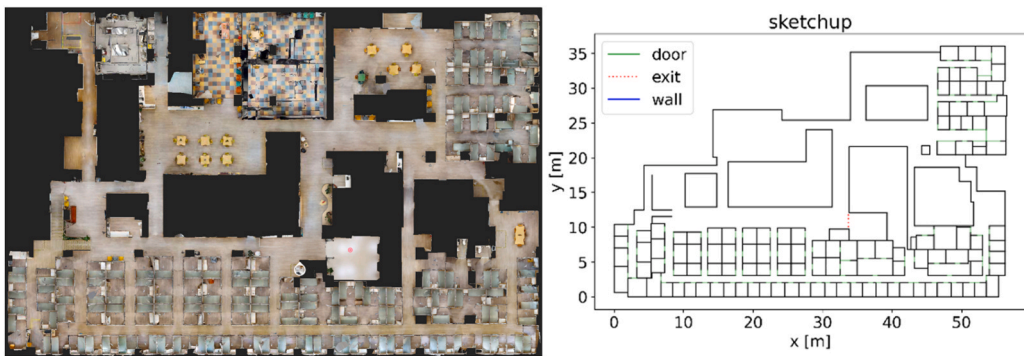


Fig. 7. (a) Layout of Yiwoyuen nursing home (Kowloon). (b) The schematic map of the simulated scene.

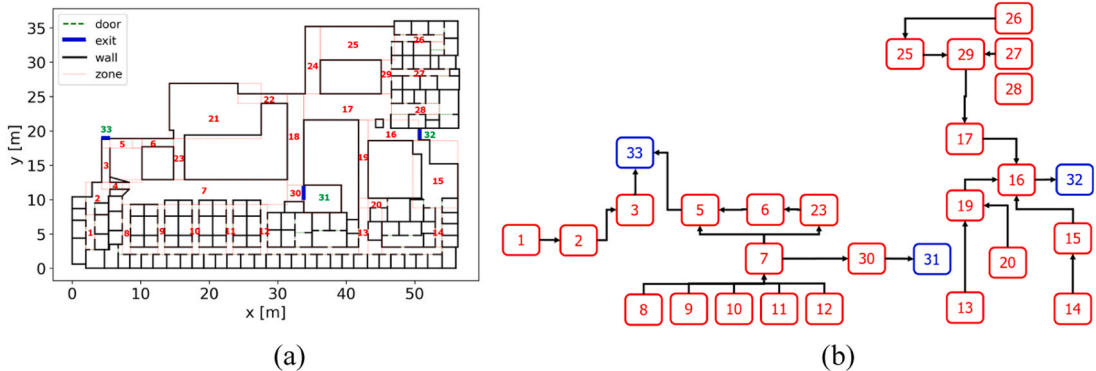


Fig. 8. The evacuation route guidance of residents in different zones. The older people and staff evacuate from their rooms to the corridors (marked in red) and then move through the corridors to the exit. (a) The discretized regions of the nursing home. (b) The evacuation route of the nursing home.

illustrates the distribution of evacuation times for five caregiver-to-resident ratios (ranging from 0.2 to 1.0) under three conditions: (1) no wheelchair users, (2) wheelchair users located near exits, and (3) wheelchair users located far from exits.

Fig. 10 shows that in both Conditions 1 and 2, as the caregiver-to-resident ratio increases, the evacuation time also increases. In contrast, in condition 3, the caregiver ratio shows no obvious influence on evacuation time. Interestingly, although every resident could move independently, evacuation time in Condition 1 (no wheelchair users) was longer than in Conditions 2 and 3.

The Tukey HSD test shown in Table C1.1 revealed significant differences in overall evacuation time among the three conditions. Specifically, the mean evacuation time in Condition 2 and Condition 3 were significantly shorter than in Condition 1 ($p < 0.001$), while the difference between Condition 2 and 3 was not statistically significant ($p = 0.37$). These results indicate that the presence of a

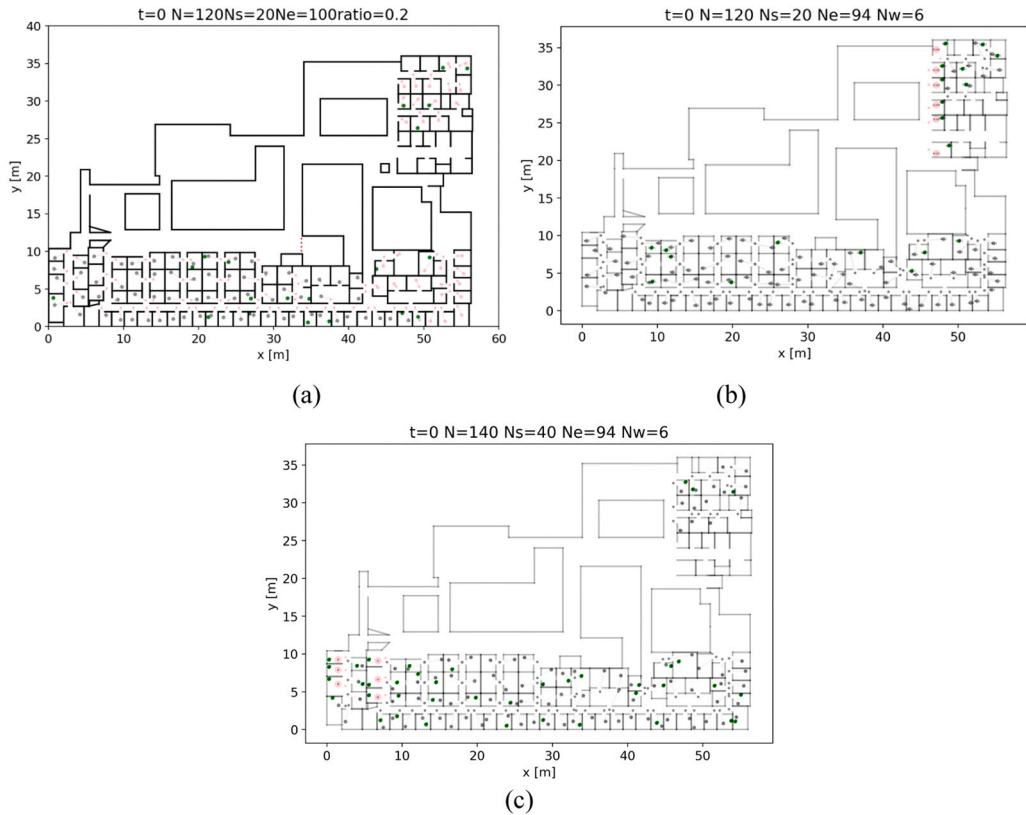


Fig. 9. Initial distribution of residents and caregivers. (a) No wheelchair users. (b) Wheelchair users with initial positions near the exit. (c) Wheelchair users with initial positions far from the exit. Note that in the subfigures, red circles represent the wheelchair users, grey circles represent the residents with full mobility and green circles represent the caregivers.

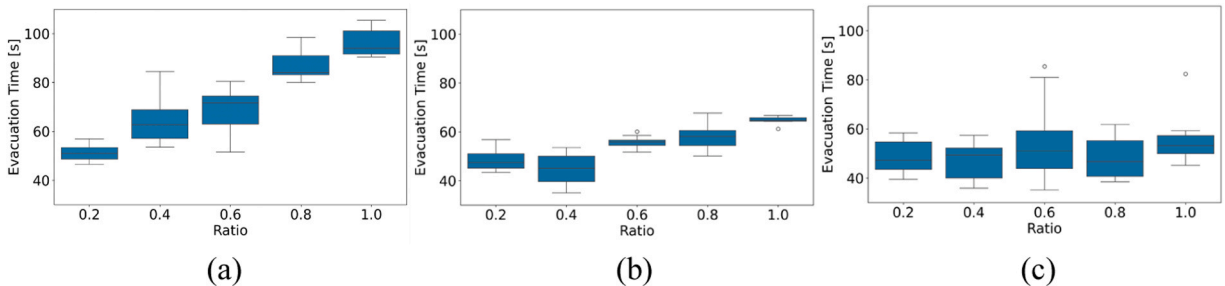


Fig. 10. Distribution of evacuation time under different caregiver-to-resident ratios across three conditions. (a) no wheelchair users, (b) wheelchair users located near exits, and (c) wheelchair users located far from exits.

wheelchair substantially reduces overall evacuation time, whereas the wheelchair’s proximity to the exit does not show a significant effect.

This counterintuitive result might be due to the random and uncoordinated distribution of agents, which leads to increased movement conflicts, congestion at blocking points, and inefficient crowd dynamics. In Condition 2 and Condition 3, however, wheelchair users were positioned alongside caregivers who could provide immediate assistance. This proximity enabled a fast and more coordinated evacuation, minimizing the delays typically associated with mobility issues. The caregiver-wheelchair pairs acted as stable evacuation units, reducing the unpredictability and chaos. Therefore, although these conditions involved individuals with physical limitations, the presence of dedicated staff nearby helped maintain a smoother, more controlled evacuation flow. This finding highlights that spatial pairing vulnerable individuals with caregivers can significantly improve evacuation performance, even compensating for the inefficiency of uncoordinated residents with full mobility. In Conditions 2 and 3, despite the presence of individuals with physical limitations, the evacuation efficiency is relatively high, benefiting from more structured spatial arrangements and coordinated evacuation with the assistance of caregivers.

Further, one-way ANOVA tests and Tukey HSD post hoc comparisons were conducted to assess the effect of caregiver-to-resident ratio on evacuation time under three distinct conditions. Detailed test results are available in Appendix C. As shown in Table C1.2 and Table C1.3, in Condition 1 (no wheelchair users), evacuation time increases significantly as the caregiver ratio rises from 0.2 to 1.0 ($p < 0.001$). Tukey HSD post hoc comparisons confirms that the pairwise differences between low (0.2–0.4) and high (0.8–1.0) ratios were statistically significant. These results indicate that an excessive number of caregivers in a crowded space may hinder movement and reduce evacuation efficiency.

In Condition 2 (wheelchair users located near exits), as shown in Table C1.4 and Table C1.5, the influence of the caregiver-to-resident ratio remain statistically significant ($p < 0.001$). Tukey HSD analysis results show that evacuation time at higher ratios (0.6–1.0) are significantly longer than that at lower ratios (0.2–0.4), indicating a decreasing return on assistance from caregivers. This suggests that, even with spatially optimized layouts for vulnerable individuals (wheelchair users), excessive staffing levels may introduce a congestion effect, thereby affecting the overall evacuation efficiency.

In Condition 3 (wheelchair users located far from exits), as shown in Table C1.6 and Table C1.7, caregiver ratio shows no significant effect on evacuation time ($p = 0.23$). Pairwise comparisons show no statistical significance, indicating that physical layout restrictions rather than staffing levels are the main factors affecting evacuation efficiency.

Finally, as shown in Table C1.8, a two-way ANOVA test reveals significant main effects of both condition ($p < 0.001$) and the caregiver ratio ($p < 0.001$), as well as a significant interaction between them ($p < 0.001$). The interaction effect indicates that the influence of caregiver ratio on evacuation performance is conditionally dependent. In particular, while higher caregiver ratios negatively impact evacuation in Conditions 1 and 2, they have no obvious effect in Condition 3. This finding suggests that staff allocation strategies should be adjusted according to the spatial configuration, and that optimizing resident layout, especially for wheelchair users, may have a greater impact on evacuation efficiency than simply increasing the number of caregivers.

3.3. Speed distribution

Fig. 11 illustrates the distribution of individual speeds across varying caregiver-to-resident ratios under three conditions: (1) no wheelchair users, (2) wheelchair users located near exits, and (3) wheelchair users located far from exits. Across all three conditions, as the caregiver-to-resident ratio increases from 0.2 to 1.0, the median individual speed decreases. In Condition 1, a slight decrease in median speed is observed as the ratio increases, suggesting that a higher caregiver presence does not necessarily improve evacuation efficiency, potentially due to increased crowd density or coordination complexity. The presence and location of wheelchair users have a more obvious effect on speed distribution. In Condition 2 and Condition 3, the median speeds are generally higher compared to that in Condition 1.

One-way ANOVA test results reveal significant effects of caregiver-to-resident ratio on individual mean speed across all three conditions (Condition 1: $F = 3845.35$, $p < 0.0001$; Condition 2: $F = 1550.78$, $p < 0.001$; Condition 3: $F = 611.80$, $p < 0.001$). Post-hoc Tukey HSD tests show that, in general, mean speed decreases as the ratio increases. Detailed test results can be seen in Table C2.1 to C2.3 in Appendix C. In Condition 1, all pairwise differences were significant, with the largest decrease observed between the ratios 0.2 and 1.0 (mean difference = -0.33 , 95 % CI: -0.34 to -0.32). In Condition 2, all pairwise differences were significant except between ratios 0.2 and 0.6, and in Condition 3, all comparisons were significant except between ratios 0.8 and 1.0. These findings suggest that higher caregiver-to-resident ratios consistently lead to slower individual speeds, likely due to the added complexity of coordination and higher crowd density.

Fig. 12 shows the interaction influence of condition and ratio on average individual speed. The effect of caregiver-to-resident ratio on speed varies significantly across conditions. In Condition 1, increasing the ratio leads to a sharp decline in mean speed, suggesting that additional caregivers may introduce coordination complexity when no wheelchair users are present. In Conditions 2 and 3, the mean speed remains relatively stable across ratios, with only minor variations. Both conditions exhibit consistently higher speeds than Condition 1, indicating that the presence and spatial placement of wheelchair users facilitate smoother crowd movement in this study. The diverging slopes among the three curves highlight a clear interaction effect between condition and ratio, consistent with the statistical findings shown in Table. C2.4 in Appendix C.

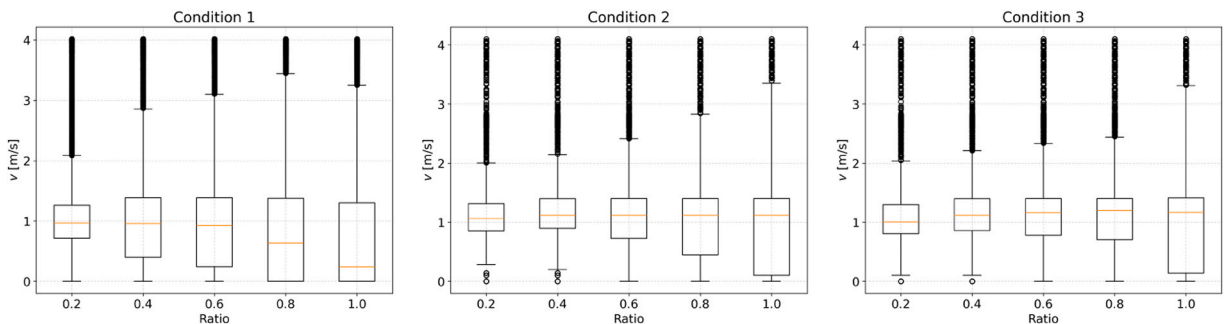


Fig. 11. Distribution of individual speed under different caregiver-to-resident ratios across three conditions. (a) no wheelchair users, (b) wheelchair users located near exits, and (c) wheelchair users located far from exits.

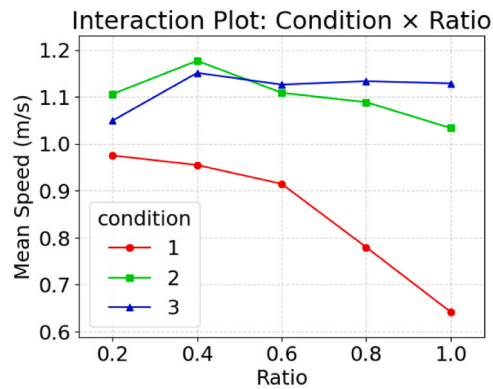


Fig. 12. The interaction between caregiver-to-resident ratio and the spatial distribution of wheelchair users (Condition) on average movement speed. Condition 1 represents the scenario without wheelchair users, Condition 2 corresponds to wheelchair users located near exits, and Condition 3 denotes wheelchair users located far from exits.

A two-way ANOVA was conducted to analyze the main effects of condition and ratio, as well as the interaction between them. The results showed significant main effects for both condition ($F = 325.47$, $p < 0.001$) and ratio ($F = 32.08$, $p < 0.001$), and a significant interaction effect between the two factors ($F = 19.24$, $p < 0.001$). The interaction effect suggests that the influence of the caregiver-to-resident ratio on speed is dependent on the spatial arrangement of wheelchair users. Post-hoc Tukey HSD (Table C2.5) comparisons further reveal that Conditions 2 and 3 do not significantly differ from each other ($p = 0.73$), while both have significantly higher speeds than Condition 1 ($p < 0.001$). Regarding ratio (Table C2.6), only comparisons involving the highest ratio (1.0) showed significant decreases in mean speed relative to the lower ratios (0.2, 0.4, 0.6), indicating that assigning too many caregivers can reduce overall movement efficiency.

These results collectively demonstrate that both the presence and spatial location of wheelchair users, as well as the caregiver-to-resident ratio, jointly shape the movement dynamics of crowds. The spatial arrangement of vulnerable individuals, combined with a well-calibrated caregiver-to-resident ratio, plays a crucial role in optimizing evacuation performance.

4. Discussion, limitation and future work

4.1. Discussion

Contrary to common expectations, the simulation results reveal that the presence of wheelchair users does not lead to longer evacuation time. While it is commonly assumed that mobility-impaired individuals (like wheelchair users) hinder overall evacuation efficiency, our results demonstrate that evacuation time in the condition without wheelchair users (Condition 1) are actually the longest. This result can be attributed to the completely random distribution of residents with full-mobility, which lead to unstructured, competitive movement and severe congestion near exits. In contrast, Conditions 2 and 3 include wheelchair users placed in designated areas, accompanied by caregivers able to provide immediate assistance. The presence of caregivers near those who cannot move independently and need assistance allows for immediate response, reduces hesitation time, and enables wheelchair users to move more smoothly and quickly.

This structured setup reduces congestion, promotes smoother flow, and allows for more coordinated evacuation behaviors. Furthermore, analysis of individual speed distributions show that Condition 1 exhibits a significant decrease in speed with increasing caregiver-to-residents ratio, reflecting coordination challenges. Conditions 2 and 3 maintain relatively stable and higher speeds across ratios, indicating that structured placement of wheelchair users, combined with caregiver support, facilitates smoother crowd movement.

Statistical analysis confirms these observations. One-way ANOVA results show that caregiver ratio significantly affected evacuation time in Conditions 1 and 2, but not in Condition 3. Tukey HSD comparisons indicate that evacuation time increase with increasing caregiver ratios, especially when it exceeds 0.4. This suggests that although caregivers are essential for helping vulnerable individuals, an excessive number of them may increase congestion and reduce evacuation efficiency. In Condition 3, the caregiver ratio shows no significant effect, implying that spatial distance to the exits is the main limiting factor, and staff availability could not compensate for poor layout design. Moreover, two-way ANOVA test results reveal significant main effects of both the condition and caregiver-to-ratio on mean speed and evacuation time, as well as a significant condition \times ratio interaction. Post hoc comparisons indicate that Conditions 2 and 3 do not differ significantly in speed or evacuation time, while both conditions outperform Condition 1. Regarding the ratio, excessive assignment (ratio = 1.0) reduces individual speed and increases evacuation time, particularly in Condition 1, suggesting that too many caregivers can create congestion instead of improving efficiency. In Condition 3, the caregiver ratio shows a limited effect, implying that spatial distance from exits becomes the dominant limiting factor, which cannot be fully compensated by adding additional caregivers.

These findings have important implications for evacuation planning in elderly care facilities. Rather than uniformly increasing

caregiver numbers, it is more effective to optimize the spatial positioning of residents in need of assistance and match them with designated caregivers. For example, placing wheelchair users near the exits and assigning them caregivers can generate a more organized flow and reduce congestion. In addition, the density of caregivers need to be controlled carefully to avoid overcrowding, particularly in facilities with narrow corridors or few exits.

Based on the simulation results, mobility limitations of residents or the caregiver-to-resident ratios influence evacuation efficiency, but their effects are strongly conditioned by spatial configuration and coordination mechanisms. The results observed in the conditions involving wheelchair users should not be directly generalized to all nursing home settings. Different spatial configurations, caregiver-to-resident ratios, and mobility patterns in other settings could lead to different results. These findings can inform staffing requirements and layout planning under local fire safety regulations, highlighting that optimal caregiver allocation depends on both resident mobility and spatial layout. Further research is needed to explore how these strategies and layouts perform in other contexts.

4.2. Limitations

Although the results of this study provide valuable insights, several limitations should be acknowledged. Firstly, agent behaviors are modeled with simplified and idealized assumptions, which may not capture all the complexities of real-life evacuations. For instance, the model does not account for emotional or psychological factors that might influence the behavior of residents or caregivers during an emergency. Secondly, the study assumes that caregivers always act optimally in assisting residents, without considering potential human errors or delays in decision-making. Thirdly, the simulation is based on a fixed nursing home layout, which may not reflect the variety of real-world designs or the unique needs of different facilities. Future work should explore the impact of varying layouts, exit numbers, and crowd densities on evacuation efficiency. Moreover, in this model, caregivers perform rescue operations based on proximity to the residents in need. However, alternative rescue strategies could be explored to further improve evacuation efficiency. For instance, rescuers might prioritize assisting residents with the least mobility (those with the lowest expected speed) or those located furthest from the exits. These alternative strategies could potentially lead to different evacuation outcomes, particularly in complex or crowded settings.

4.3. Future work

Future research could extend this study in several ways. First, incorporating a more detailed model of human behavior, such as factors influencing decision-making under stress or the effect of caregiver fatigue, could enhance the realism of the simulation. Second, testing the model in a variety of nursing home layouts, including those with different exit configurations or corridor widths, would provide further insights into the influence of spatial design on evacuation efficiency. Besides, while this study only focus on single-floor evacuations, future research can extend to multi-floor evacuations, considering the challenges of vertical movement, stair congestion, caregiver fatigue, and wheelchair accessibility. Additionally, incorporating real-world data from actual evacuations in elderly care facilities would help validate the model and refine its assumptions. Finally, exploring alternative evacuation strategies, such as dynamic adjustments to caregiver deployment based on real-time conditions, could improve the adaptability of the evacuation plan and better prepare facilities for unforeseen challenges.

5. Conclusion

This study proposes an enhanced agent-based model to simulate caregiver-assisted evacuations of older residents in the nursing home, investigating how caregiver-to-resident ratio and spatial configuration of residents without mobility influence evacuation efficiency. Based on simulation results, evacuation performance is not determined solely by mobility status of residents nor caregiver-to-resident ratios, but rather by the interaction between spatial layout and caregiver support. The scenario of residents with full mobility yield the longest evacuation time due to disorganized pedestrian flow and congestion. Meanwhile, scenarios involving wheelchair users paired with nearby caregivers demonstrate more structured and efficient evacuation.

Statistical analysis results confirm that excessive caregiver ratios can hinder evacuation. A moderate caregiver-to-resident ratio (0.2–0.4) is generally beneficial under the simulated configuration, where all residents are full mobility or only a few wheelchair users are considered. Furthermore, a significant interaction effect between caregiver ratio and layout condition emphasize that staffing decisions should consider the environment.

These findings emphasize the importance of comprehensive evacuation planning that considers not only staff allocation but also architectural design, spatial logic, and vulnerable resident placement. The insights gained in this study can inform both policy and practice, guiding safer, more efficient emergency planning in long-term care settings.

CRedit authorship contribution statement

Jacqueline Tsz Yin LO: Writing – review & editing, Supervision, Project administration, Funding acquisition. **Hongliu LI:** Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to

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Appendix A. Literature Review Table

Table A1
Summary of simulation-based studies on older people evacuation in care facilities

Study	Model Type	Older People Features	Caregiver Role	Key Limitation
[15]	ABM, CA	Reduced mobility	Included	Lacks assistance modeling
[16]	CA	Non-self-evacuating patients	Included	Fixed staff number
[17]	CA	Heterogeneous mobility	Included	No crowd interaction
[18]	ABM	Reduced mobility	Not included	Does not simulate interaction effects
[19]	CA	Reduced mobility	Included	Fixed staff number
[20]	ABM	Requires assistance	Included	No social interactions between crowds.
[21]	ABM	Requires assistance	Included	No modeling of counter-flow or return trips
[22]	ABM	Disabled older adults	Included	No self-sufficient older adults.
[23,24]	ABM	Risk of falling	Not included	No assistance or complex layout
[25]	Multi-agent	Disabled people	Partial assistance	No modeling of caregiver decisions
[26]	Agent-based	Fatigue, mobility	Not included	Focus on environment navigation
[27]	CA	reduced mobility	Not included	No assistance
[28]	Pathfinder	Heterogeneous mobility	Included	Stair/Elevator-specific optimization only
[29]	AnyLogic	Reduced mobility	Not included	Static route assignment
[30]	Pathfinder	Heterogeneous mobility	Not included	No caregiver involvement
[31]	ABM	Reduced mobility	Not included	No caregiver involvement
[32]	Pathfinder	Heterogeneous mobility	Included	Fixed staffing level
[33]	MassMotion	reduced mobility	Not included	No assistance
[34]	Pathfinder	reduced mobility	Not included	No assistance
This study	ABM	Heterogeneous mobility	Included	Models realistic caregiver-elderly interactions and routing

Appendix B. Model Credibility

Table. B1
Comparison of experimental and simulated evacuation time across different bottleneck widths

b [m]	Expt Time [s]	Sim Mean± Std [s]	95 % CI of Sim	Absolute Error [s] (Relative Error [%])	Exp. in 95 % CI?	Exp. in ±1σ?	Exp. in ±2σ?
1.0	37.2	37.63 ± 1.03	[36.892, 38.368]	0.43 (1.16)	Yes	Yes	Yes
1.2	31.4	32.44 ± 2.33	[30.775, 34.105]	1.04 (3.31)	Yes	Yes	Yes
1.4	27.7	27.27 ± 1.46	[26.223, 28.317]	0.43 (1.55)	Yes	Yes	Yes
1.6	23.8	24.54 ± 0.45	[24.218, 24.862]	0.74 (3.11)	No	No	Yes

Note: Significant reproducibility (expt within 95 % CI and error <10 %). Good reproducibility (expt within 2σ and error <15 %).

Appendix C. ANOVA and Post-hoc Analyses

C1: Evacuation Time

Table C1.1
Tukey HSD test comparing overall evacuation time across the three environmental conditions

Group1	Group2	meandiff	p	lower	upper	reject
no_wheelchair	wheelchair_far_exit	-22.632	0.0	-28.7431	-16.5209	True
no_wheelchair	wheelchair_near_exit	-19.162	0.0	-25.2731	-13.0509	True
wheelchair_far_exit	wheelchair_near_exit	3.47	0.373	-2.6411	9.5811	False

Note: p < 0.001 indicates statistical significance

Table C1.2

One-way ANOVA results for evacuation time under Condition 1 (no wheelchair users) across different caregiver-to-resident ratios

	Sum_sq	Df	F	p
C(ratio)	13,020.58	4.0	62.52	8.43e-18
Residual	2342.93	45.0	-	-

Note: $p < 0.001$ indicates statistical significance

Table C1.3

Tukey HSD test results for evacuation time under Condition 1 (no wheelchair users) across different caregiver-to-resident ratios

Group1	Group2	meandiff	p	lower	upper	reject
0.2	0.4	13.25	0.0015	4.0809	22.4191	True
0.2	0.6	17.45	0.0	8.2809	26.6191	True
0.2	0.8	35.95	0.0	26.7809	45.1191	True
0.2	1.0	44.95	0.0	35.7809	54.1191	True
0.4	0.6	4.2	0.6916	-4.9691	13.3691	False
0.4	0.8	22.7	0.0	13.5309	31.8691	True
0.4	1.0	31.7	0.0	22.5309	40.8691	True
0.6	0.8	18.5	0.0	9.3309	27.6691	True
0.6	1.0	27.5	0.0	18.3309	36.6691	True
0.8	1.0	9.0	0.0567	-0.1691	18.1691	False

Note: $p < 0.001$ indicates statistical significance

Table C1.4

One-way ANOVA test results for evacuation time under Condition 2 (wheelchair users near exit) across different caregiver-to-resident ratios

	Sum_sq	Df	F	p
C(ratio)	2526.5788	4.0	31.357921	1.705704e-12
Residual	906.4380	45.0	NaN	NaN

Note: $p < 0.001$ indicates statistical significance

Table C1.5

Tukey HSD test results for evacuation time under Condition 2 (wheelchair users near exit) across different caregiver-to-resident ratios

Group1	Group2	meandiff	p	lower	upper	reject
0.2	0.4	-3.6	0.3899	-9.3032	2.1032	False
0.2	0.6	7.37	0.0055	1.6668	13.0732	True
0.2	0.8	9.83	0.0001	4.1268	15.5332	True
0.2	1.0	16.39	0.0	10.6868	22.0932	True
0.4	0.6	10.97	0.0	5.2668	16.6732	True
0.4	0.8	13.43	0.0	7.7268	19.1332	True
0.4	1.0	19.99	0.0	14.2868	25.6932	True
0.6	0.8	2.46	0.7366	-3.2432	8.1632	False
0.6	1.0	9.02	0.0004	3.3168	14.7232	True
0.8	1.0	6.56	0.0169	0.8568	12.2632	True

Note: $p < 0.001$ indicates statistical significance

Table C1.6

One-way ANOVA test results for evacuation time under Condition 3 (wheelchair users far from exit) across different caregiver-to-resident ratios

	Sum_sq	Df	F	p
C(ratio)	658.5368	4.0	1.473855	0.225979
Residual	5026.6410	45.0	NaN	NaN

Note: $p < 0.001$ indicates statistical significance

Table C1.7

Tukey HSD test results for evacuation time under Condition 3 (wheelchair users far from exit) across different caregiver-to-resident ratios

Group1	Group2	meandiff	p	lower	upper	reject
0.2	0.4	-1.4	0.9983	-14.8304	12.0304	False
0.2	0.6	6.62	0.6305	-6.8104	20.0504	False
0.2	0.8	-0.15	1.0	-13.5804	13.2804	False
0.2	1.0	7.02	0.5772	-6.4104	20.4504	False
0.4	0.6	8.02	0.4462	-5.4104	21.4504	False
0.4	0.8	1.25	0.9989	-12.1804	14.6804	False
0.4	1.0	8.42	0.3968	-5.0104	21.8504	False

(continued on next page)

Table C1.7 (continued)

Group1	Group2	meandiff	p	lower	upper	reject
0.6	0.8	-6.77	0.6105	-20.2004	6.6604	False
0.6	1.0	0.4	1.0	-13.0304	13.8304	False
0.8	1.0	7.17	0.5572	-6.2604	20.6004	False

Note: $p < 0.001$ indicates statistical significance

Table C1.8

Two-way ANOVA results examining the main and interaction effects of condition and caregiver-to-resident ratio on evacuation time

	sum_sq	df	F	p
C(condition)	14857.176133	2.0	121.176765	7.362262e-31
C(ratio)	10294.047067	4.0	41.979691	7.808070e-23
C(condition):C(ratio)	5911.648533	8.0	12.054014	6.806360e-13
Residual	8276.004000	135.0	NaN	NaN

Note: $p < 0.001$ indicates statistical significance

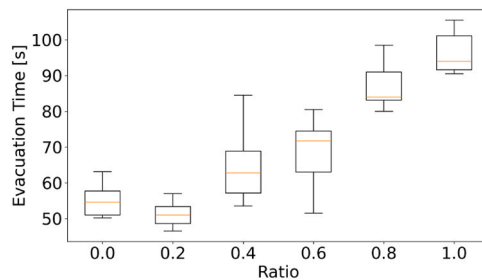


Figure C1.1 Distribution of evacuation time under different caregiver-to-resident ratio in Condition 1

Figure C1.1 shows the distribution of evacuation time, including the additional condition with a caregiver-to-resident ratio of 0. In the absence of caregivers (ratio = 0.0), the evacuation time is observed to be longer compared to the ratio = 0.2 condition. A series of pairwise comparisons were conducted to assess the differences between the baseline condition (ratio = 0.0) and the other ratio groups. The results reveal significant differences across all comparisons. The ratio = 0 condition shows significant differences when compared to ratio = 0.2 ($p < 0.05$), ratio = 0.4 ($p < 0.05$), ratio = 0.6 ($p < 0.05$), ratio = 0.8 ($p < 0.05$), and ratio = 1.0 ($p < 0.05$). These findings emphasize the necessity of having caregivers in the nursing home, although an excessive number of caregivers may hinder the evacuation process.

C2: Individual Speed

Table C2.1

Tukey HSD Multiple Comparisons of Individual Speed Across Different Ratios under Condition 1

group1	group2	meandiff (g2-g1)	p-adj	lower	upper
0.2	0.4	-0.029	0.0*	-0.0404	-0.0177
0.2	0.6	-0.0639	0.0*	-0.0748	-0.0529
0.2	0.8	-0.1965	0.0*	-0.207	-0.1861
0.2	1.0	-0.3339	0.0*	-0.3439	-0.3238
0.4	0.6	-0.0348	0.0*	-0.0448	-0.0249
0.4	0.8	-0.1675	0.0*	-0.1769	-0.1581
0.4	1.0	-0.3048	0.0*	-0.3138	-0.2959
0.6	0.8	-0.1326	0.0*	-0.1415	-0.1238
0.6	1.0	-0.27	0.0*	-0.2784	-0.2616
0.8	1.0	-0.1373	0.0*	-0.1451	-0.1296

Table C2.2

Tukey HSD Multiple Comparisons of Individual Speed Across Different Ratios under Condition 2

group1	group2	meandiff	p-adj	lower	upper
0.2	0.4	0.069	0.0	0.063	0.0751
0.2	0.6	0.0001	1.0	-0.0056	0.0059
0.2	0.8	-0.022	0.0	-0.0276	-0.0164
0.2	1.0	-0.0755	0.0	-0.081	-0.0701
0.4	0.6	-0.0689	0.0	-0.0744	-0.0634
0.4	0.8	-0.091	0.0	-0.0963	-0.0857
0.4	1.0	-0.1446	0.0	-0.1497	-0.1394
0.6	0.8	-0.0221	0.0	-0.0271	-0.0172
0.6	1.0	-0.0756	0.0	-0.0804	-0.0709
0.8	1.0	-0.0535	0.0	-0.0581	-0.049

Table C2.3

Tukey HSD Multiple Comparisons of Individual Speed Across Different Ratios under Condition 3

group1	group2	meandiff	p-adj	lower	upper
0.2	0.4	0.1009	0.0	0.095	0.1068
0.2	0.6	0.0709	0.0	0.0652	0.0765
0.2	0.8	0.0783	0.0	0.0728	0.0839
0.2	1.0	0.0776	0.0	0.0722	0.0829
0.4	0.6	-0.0301	0.0	-0.0355	-0.0246
0.4	0.8	-0.0226	0.0	-0.0278	-0.0173
0.4	1.0	-0.0234	0.0	-0.0285	-0.0182
0.6	0.8	0.0075	0.0004	0.0025	0.0125
0.6	1.0	0.0067	0.0014	0.0019	0.0115
0.8	1.0	-0.0008	0.9902	-0.0054	0.0038

Table C2.4

Two-way ANOVA results for Condition and Ratio on individual speed

Source	Sum Sq	df	F	p-value
Condition	2.20897	2	325.47	2.28×10^{-52}
Ratio	0.43540	4	32.08	8.85×10^{-9}
Condition \times Ratio	0.52219	8	19.24	4.40×10^{-19}
Residual	0.45812	135	-	-

Note: *** indicates $p < 0.001$.

Table C2.5

Tukey HSD post-hoc comparison for Condition of individual speed

Group 1	Group 2	Mean Diff	Adj. p-value
1	2	0.2496	< 0.001
1	3	0.2646	< 0.001
2	3	0.0150	0.726

Table C2.6

Tukey HSD post-hoc comparison for Ratio of individual speed

Group 1	Group 2	Mean Diff	Adj. p-value
0.2	0.4	0.0507	0.677
0.2	0.6	0.0062	1.000
0.2	0.8	-0.0430	0.795
0.2	1.0	-0.1089	0.040*
0.4	0.6	-0.0445	0.773
0.4	0.8	-0.0937	0.109
0.4	1.0	-0.1596	0.0005*
0.6	0.8	-0.0492	0.702
0.6	1.0	-0.1151	0.026*
0.8	1.0	-0.0660	0.424

Data availability

Data will be made available on request.

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