

Construction of a Cellular Automata-Based Fire Evacuation Model for Ordinary Supermarkets (Postprint)

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Date: 2018-08-13T00:00:00+00:00

Abstract

By analyzing existing cellular automata theory and incorporating the characteristics of pedestrian evacuation, a fire evacuation model for ordinary supermarkets was constructed that considers exit attraction, fire repulsion force, friction force, repulsive force, and herding attraction. The model fully accounts for the influence of multiple factors on the evacuation process, normalizes these influencing factors, and employs the cellular transition intensity established from the comprehensive influencing factors as the pedestrian movement rule. The effects of evacuation population, exit width and separation distance, and herding psychology on evacuation time were investigated, and the model was validated using the simulation evacuation software Pathfinder+FDS, demonstrating that the evacuation model possesses certain credibility. The research indicates that pedestrian evacuation time exhibits a linear positive correlation with population size, with a critical threshold for population; evacuation time becomes relatively shorter as exit width increases or as more exits are available, with minimal impact on evacuation time once the exit threshold is reached; and appropriate herding behavior in unfamiliar evacuation environments or emergency situations can improve evacuation efficiency.

Full Text

Preamble

Title: Construction of Fire Evacuation Model for Ordinary Supermarkets Based on Cellular Automata

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Abstract: By analyzing existing cellular automata theory and incorporating the characteristics of crowd evacuation, this paper constructs an ordinary supermarket fire evacuation model that considers exit attractiveness, fire repulsion, friction, repulsion forces, and herding attraction. The model comprehensively accounts for multiple factors influencing the evacuation process, normalizes these influencing factors, and employs cellular transfer intensity—established through comprehensive influencing factors—as the pedestrian movement rule. The study investigates the effects of supermarket evacuation population, exit width and separation distance, and herding psychology on evacuation time, and validates the model using the evacuation simulation software Pathfinder+FDS, demonstrating its credibility.

The research shows that pedestrian evacuation time exhibits a linear positive correlation with the number of evacuees, with a critical threshold value for population size. Wider exits or more exits generally lead to shorter evacuation times, though once an exit threshold is reached, the impact on evacuation time becomes insignificant. In unfamiliar evacuation environments or emergency situations, appropriate herding behavior can improve evacuation efficiency.

Keywords: cellular automata; cell transfer intensity; herding attraction; fire evacuation model

0 Introduction

In recent years, fire accidents have occurred frequently in China, such as the massive Tianjin Port fire and explosion on August 12, the serious fire at Henan Lushan Kangleyuan Elderly Apartment, and the November 18 fire in Beijing's Daxing district. Particularly in large public places where people are relatively concentrated and building structures are complex, evacuation is difficult. Whether groups can evacuate quickly and safely during a fire directly affects lives and property. How to achieve rapid and safe evacuation in fire scenarios is a problem worthy of study [1-4].

Currently, domestic and international research on evacuation focuses primarily on evacuation model establishment and evacuation path planning. Common crowd evacuation models include the social force model, magnetic field model, lattice gas model, and cellular automata model. Wan et al. [5] proposed a model combining social forces with Gaussian plume theory to study the impact of sudden toxic gas release on evacuation speed and casualties in subway stations. Guo et al. [6] combined CA models with lattice gas models to simulate pedestrian evacuation, investigating the effects of pedestrian density and exit congestion on the evacuation process. Yue et al. [7] established a CA model for scenarios with impaired visibility and no panic trampling behavior, conducting simulation studies on pedestrian evacuation flow. Hu et al. [8] proposed a three-dimensional space CA model to study collisions during pedestrian movement in 3D space, verifying the “faster-is-slower” phenomenon. Li et al. [9] improved the CA model

by defining a pedestrian's fuzzy visual field, which effectively produced initial non-uniform pedestrian self-organization phenomena.

Path planning algorithms mainly include A* algorithm, Dijkstra algorithm, Floyd algorithm, ant colony algorithm, and particle swarm algorithm. Wang et al. [10] established a CA model based on improved ant colony algorithm, modifying the heuristic function and taboo rules in the ACO algorithm, with results showing the model could quickly find optimal paths. Tsai et al. [11] proposed a PSO-based evacuation simulation framework that could adapt to various scenario changes such as evacuation population, obstacles, exits, and signage. Duan et al. [12] used genetic algorithm crossover and mutation to improve pheromone updating in ant colony algorithms, studying path optimization problems in large-scale venue evacuation. Crowd evacuation is a complex process involving multiple factors including fire environment, personnel psychology, and evacuation behavior. However, the aforementioned studies did not comprehensively consider the impact of multiple influencing factors on the evacuation process.

This paper establishes an evacuation model based on cellular automata that fully considers group psychological characteristics and behaviors during evacuation, simulates the supermarket evacuation process, and provides a basis for more effective exit and layout configurations to improve evacuation efficiency.

1 Simulation Model Establishment

The two-dimensional plane is divided into identical grids, where each grid represents a cell. Grids can be in two states: occupied by obstacles or people, or empty. In the model, each cell is divided into a $0.4\text{m} \times 0.4\text{m}$ grid, with each evacuee occupying one cell during evacuation. Pedestrian speed during evacuation is 1.0 m/s , with each time step being 0.4 s . Within each time step, a person can only move to one adjacent cell. The neighborhood type adopts the Moore-type orthogonal grid, where cells in each time step move toward one of eight unoccupied neighboring cells or remain stationary based on certain transfer intensities. The cell transfer directions are shown in Figure 1 [Figure 1: see original paper]. The fire spread model uses an extended Moore type as shown in Figure 2 [Figure 2: see original paper].

1.1 Cell Transfer Intensity Calculation

During evacuation, pedestrians follow certain walking rules, with behaviors dynamically adjusted at each step according to the surrounding environment. Two fundamental issues must be addressed in cell movement: first, the pedestrian turning problem, which this paper resolves by using cellular transfer intensity influenced by exit attractiveness, fire repulsion, friction, repulsion forces, and herding attraction to determine turning direction; second, when multiple people

compete for the same position, the occupant with greater competitiveness takes the position.

Emergency evacuation targets safe exits, with evacuees choosing the nearest path to exit. Exit attractiveness is positively correlated with proximity to the exit—cells closer to the exit exert greater attraction on evacuees, corresponding to larger values. Euclidean distance from the evacuee's position to the exit is used as the exit attractiveness measure. When exit width exceeds one cell, the nearest cell position to the exit is used for distance calculation. With multiple evacuation exits, the minimum Euclidean distance to all exits is calculated. The specific formula is:

$$D_{ij} = \min_m \{ \min_n \{ \sqrt{(i - i_n^m)^2 + (j - j_n^m)^2} \} \} \quad (1)$$

where D_{ij} represents the distance from evacuee position (i, j) to the exit; (i_n^m, j_n^m) are the coordinates of exit m at position n . When obstacles exist, Dijkstra's algorithm first finds the optimal path and calculates distance, then uses formula (2) for normalization. Based on the calculated minimum distance, normalization is performed, and the exit attractiveness probability formula is:

$$P_{decide}(i, j) = \frac{D_{max} - D_{ij}}{D_{max} - D_{min}}$$

where $P_{decide}(i, j)$ is the exit attractiveness probability at position (i, j) ; D_{max} is the maximum distance to the exit among eight neighboring cells; D_{min} is the minimum distance to the exit among eight neighboring cells; and D_{ij} is the distance from position (i, j) to the exit.

Fire repulsion represents the tendency of evacuees to move away from fire during evacuation. Euclidean distance from cells to the hazard source is calculated to introduce repulsion probability:

$$P_{fire}(i, j) = -\frac{F_{ij} - F_{min}}{F_{max} - F_{min}}$$

where $P_{fire}(i, j)$ is the repulsion probability of cell (i, j) ; F_{max} is the farthest Euclidean distance to the fire among eight neighboring cells; F_{min} is the nearest Euclidean distance to the fire among eight neighboring cells; and F_{ij} is the Euclidean distance from cell (i, j) to the fire. Positions closer to the fire source experience greater fire repulsion. Fire occurrence locations are random and randomly selected.

Following the social force model, repulsion and friction forces also exist during evacuation. Repulsion primarily occurs when multiple people compete for the same position, move in opposite directions, or avoid collisions with walls or

obstacles. Song Weiguo et al. [13] introduced exclusion and friction probabilities, which this model adopts. The repulsion probability formula is:

$$R_{ij} = 1 - e^{-V}$$

where V is pedestrian moving speed and $\mu \in [0, \infty]$ is the hardness coefficient. Greater evacuee density leads to greater collision panic and repulsion force, with $\mu=1$ (person-to-person) and $\mu=1.5$ (person-to-wall/obstacle). The normalized repulsion probability is:

$$P_r(i, j) = \frac{R_{ij} - R_{min}}{R_{max} - R_{min}}$$

Friction primarily exists between person-to-person, person-to-wall, and person-to-obstacle interactions, influenced by contact degree, relative speed, and friction coefficient. Since grid points in cellular automata are identical, contact degree is uniform. The friction probability formula is:

$$F_{ij} = \theta * V$$

$$P_f(i, j) = -\frac{F_{ij} - F_{min}}{F_{max} - F_{min}}$$

where V is pedestrian moving speed and $\theta \in [0, 1]$ is the friction coefficient, reflecting friction degree between person-to-person and person-to-wall/obstacle during evacuation, with $\theta=0.1$ (person-to-person) and $\theta=0.3$ (person-to-wall/obstacle).

Under sudden fire conditions, evacuees experience panic and tend to move toward crowded areas, primarily due to herding psychology. Herding factors significantly impact evacuation during public fires and should be considered in evacuation models. Herding attraction is related to pedestrian density within the visual field, which depends on fire size and spread, obstacles, and visibility. For simplicity, the visual field is defined as the area where $r \leq 3$, with black squares representing people. First, eight directions are determined as shown in Figure 3 [Figure 3: see original paper]. The visual field is divided into eight neighborhoods as shown in Figure 4 [Figure 4: see original paper]. During evacuation, density reflects where crowds tend to gather but cannot correctly reflect actual pedestrian flow direction. Therefore, directionality is incorporated:

$$P_{follow}(i, j, n) = \frac{N_{i,j,n}}{N_{i,j}}$$

where $N_{i,j,n}$ represents the total number of people in the visual field of the central cell at time step t at position (i,j) moving toward direction n . The formula

indicates that the more people moving in a certain direction, the greater the herding attraction to that position.

Based on the above influencing factors, cellular transfer intensity ($P(i, j)$) is calculated through:

$$P(i, j) = \beta_1 P_{decide} + \beta_2 P_{fire} + \beta_3 P_r + \beta_4 P_f + \beta_5 P_{follow} \quad (7)$$

where $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ are coefficients for each influencing factor, with $\beta_1 + \beta_2 + \beta_3 + \beta_4 + \beta_5 = 1$. Different coefficients reflect which forces dominate during evacuation, varying across different evacuation environments.

Conflict avoidance principle: When multiple people simultaneously compete for one target position during evacuation, those with greater competitiveness values are more likely to successfully occupy the position. After transfer intensity calculation, when evacuees select their next target position, multiple cells may choose the same location. In such cases, competitiveness (Comp) determines which cell occupies the position. When competitiveness differences are significant, the cell with higher Comp value occupies the position while others select alternative positions. When competitiveness differences are within (0-0.2), random selection determines the occupying cell. The competitiveness formula is:

$$Comp = \begin{cases} P.age^{18/22} - 0.3 * P.chi + (0.7 + 0.3 * P.g) & \text{if } P.age \geq 18 \\ P.age - 0.3 * P.chi + (0.7 + 0.3 * P.g) & \text{if } P.age < 18 \end{cases}$$

where $P.age$ represents age, $P.g$ is gender, and $P.chi$ indicates whether carrying a child. This formula shows competitiveness relates to age, child-carrying status, and gender—younger individuals have greater competitiveness than elderly, those carrying children have 0.3 reduced competitiveness, and males are more competitive than females.

1.2 Cellular Evacuation Process

This study examines evacuation in a two-dimensional plane, defining evacuation completion when evacuees leave the exit. The evacuation process flowchart is shown in Figure 5 [Figure 5: see original paper]. Initialization primarily involves setting evacuation plane dimensions, exits, obstacles, fire source location, and adding evacuees. Evacuation time is defined as the time when the last person evacuates, calculated as evacuation time = $t \times$ time step duration, where t is the number of evacuation steps.

Before position updating, it is necessary to check whether a cell's eight neighboring cells are occupied and calculate transfer intensities for unoccupied neighbor cells. The cell position update flowchart is shown in Figure 6 [Figure 6: see original paper]. The specific steps are:

- a) Determine transfer intensities for unoccupied neighboring cells around each cell and select the position with maximum transfer intensity as the target;
- b) When multiple people compete for the same position, calculate each competitor's competitiveness, with the most competitive occupant taking the position;
- c) Check whether the person has reached the exit—Y indicates successful evacuation, N indicates unsuccessful evacuation requiring participation in the next update;
- d) Update each person's position status and recalculate transfer intensities for neighboring cells of each unsuccessfully evacuated cell;
- e) Repeat the above steps until the last person evacuates successfully.

2 Model Simulation

Based on the established model, MATLAB software was used to program and simulate a supermarket fire evacuation process in a 32m×40m space, with experimental results analyzed. The supermarket floor plan is shown in Figure 7 [Figure 7: see original paper]. Initially, evacuee positions are randomly distributed, with fire occurring at position (8m,28m) and burning material being plastic. In the model, α , β , and γ are constant values at 10%, 5%, and 5% respectively. All experimental results are averages from multiple simulations.

The impact of supermarket layout and fire location on evacuation time was investigated. The model features similar upper and lower shelf areas with different shelf orientations. During evacuation, the lower area evacuates faster than the upper area. When the lower exit is empty while people remain at the upper exit, this indicates that shelf orientation toward the exit facilitates evacuation. Studies on fires at different locations reveal that fires occurring away from main pedestrian thoroughfares have minimal impact on evacuation, while fires on the left middle side of the supermarket affect evacuation less than those on the right side.

Simulations primarily analyze the impact of exit width, evacuation population, and herding psychology on evacuation time. Figure 8 [Figure 8: see original paper] shows the effect of single exit width on evacuation time (initial settings: 400 people, $\alpha = 50\%$, $\beta = 30\%$, centrally located exit). The data indicate that evacuation time decreases as exit width increases. When exit width reaches a certain critical value, increasing width has minimal effect on evacuation time (this critical value is termed the exit threshold). If exit width does not reach the threshold, evacuation time increases linearly with decreasing width.

Figure 9 [Figure 9: see original paper] shows the effect of double exit width on evacuation time. The data exhibit similar patterns to Figure 8, but at the same

width, double exit evacuation times are consistently shorter than single exit times, demonstrating higher evacuation efficiency for double exits. When the exit threshold is reached, increasing exit width has minimal effect on reducing evacuation time. Figure 10 [Figure 10: see original paper] illustrates the impact of distance between double exits on evacuation time, showing that when exits are within evacuation capacity range, separation distance has minimal effect on evacuation time. Therefore, exit settings should be based on actual occupancy numbers with reasonable sizing; when exit width is fixed, multiple exits should be established.

Figure 11 [Figure 11: see original paper] shows the effect of evacuation population on evacuation time under fire conditions (initial settings: double exits, 3m width, $\alpha = 50\%$, $\beta = 30\%$). Evacuation time increases linearly with population. When population is between 350-400, evacuation time increases more slowly; after 400 people, evacuation time increases more rapidly, indicating this is the critical threshold for evacuation congestion. Exceeding this population leads to slower evacuation and rapidly increasing evacuation times. Therefore, determining optimal occupancy is crucial for improving evacuation efficiency.

Figure 12 [Figure 12: see original paper] shows the effect of herding coefficient on evacuation time. Without any herding behavior, evacuation time is longer. Before 0.3, evacuation time gradually decreases as the herding coefficient increases, as some people unfamiliar with the evacuation environment benefit from following crowds. When the herding coefficient reaches 0.3, evacuation time is shortest. Subsequently, evacuation time gradually increases with the herding coefficient, as most evacuees blindly follow others, causing congestion in certain areas and reduced exit utilization, thereby affecting evacuation efficiency. Therefore, in unfamiliar environments, appropriate herding behavior facilitates evacuation, while blind following extends evacuation time.

3 Conclusion

This study establishes a group fire evacuation model based on cellular automata that captures interactions between people, obstacles, and fire environments. The model comprehensively considers factors affecting evacuation during fires, normalizes these influencing factors, and uses cellular transfer intensity as the pedestrian movement rule. The model's rationality is verified through simulation software, with evacuation times from the cellular automata model and software simulation being similar, both forming an arch-shaped evacuation pattern at exits, demonstrating model credibility.

Applying the model to supermarket evacuation simulation yields the following conclusions:

- a) Supermarket shelves hinder evacuation, with shelves oriented perpendicular to exit positions facilitating evacuation. Fires occurring on main thor-

oughfares or near exits reduce evacuation efficiency and increase detours. Supermarkets should place flammable items against walls or in relatively rear positions.

- b) Exit width settings should be based on actual supermarket pedestrian flow, with an exit threshold existing. Under equal width conditions, double exits should be adopted.
- c) Supermarket pedestrian evacuation time shows linear positive correlation with evacuation population, with a critical population threshold. Exceeding this threshold causes rapid evacuation time increase, so supermarkets should reasonably control pedestrian flow according to scale.
- d) In unfamiliar environments or under excessive tension, appropriate herding psychology helps find optimal paths and improves evacuation efficiency, but excessive or blind herding reduces exit utilization and hinders evacuation. Setting guides or signage at pedestrian intersections or exits can reduce herding psychology and help evacuees find appropriate evacuation paths and exits.

The group evacuation process is complex and critical for ensuring life safety and reducing property loss. Future work will continuously improve the model: first, to adapt to more complex scenarios, particularly multi-floor evacuation; second, to integrate cellular automata models with other models to construct models fully considering evacuation behavior, building structure, and fire environment based on multiple models and concepts.

Model validation was performed using Pathfinder+FDS evacuation software. The initial cellular automata model settings ($\alpha = 50\%$, $\beta = 30\%$, double exits, 3m width, 400 evacuees) are shown in Figure 7. After multiple simulations, the average evacuation time was 64.6s. Pathfinder+FDS simulation software was used for validation, with fire occurring at the snack shelves and heat release rate of 500kW/m². The FDS fire evacuation model simulated supermarket fire development, with fire smoke spreading radially, temperature rising sharply, and visibility decreasing. The software simulated smoke more realistically with more considered factors, while the cellular automata model features random fire diffusion enabling fire avoidance behavior. The FDS model was imported into Pathfinder, selecting Steering movement mode for simulation. At 20s simulation time as shown in Figure 13 [Figure 13: see original paper], evacuation time was 63.4s. The software simulation and model evacuation times differ minimally by 1.2s, possibly because the cellular automata model considers fire smoke impact on evacuation, but the fire location at the upper left corner minimally affects most evacuees, potentially causing slight evacuation delay. The model demonstrates certain credibility.

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