

Postprint of a Fire Evacuation Model Based on Dynamic Coupling of FDS and Cellular Automaton

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Abstract

To investigate the effects of hazard factors such as temperature, smoke, and CO concentration on evacuation in fire scenarios, a fire evacuation model based on dynamic coupling of FDS and cellular automata is established. The model establishes a one-to-one correspondence between FDS grids and cellular automata cells, and loads hazard data obtained from FDS simulations into the cells in real time through Python and other technical means, enabling hazard data to continuously influence pedestrian transition probabilities, thereby achieving dynamic coupling of disasters and evacuation. Using a single-story teaching building as the simulation scenario for analysis, factors such as fire source location and heat release rate are discussed to derive the influence patterns of these factors on pedestrian evacuation processes. The model is compared with traditional software and similar schemes to identify their similarities and differences. Research shows that high temperatures and smoke caused by fire affect pedestrians' choices of evacuation routes and emergency exits; the greater the heat release rate, the earlier pedestrians are exposed to hazardous conditions, and the more pedestrians are simultaneously in a hazardous state. Compared with traditional evacuation software, this model not only considers the dynamic impact of fire-generated hazard factors on pedestrian evacuation, but also can determine the location and time when pedestrians first enter a hazardous state, and visualize these results.

Full Text

Preamble

Fire Evacuation Model Based on Dynamic Coupling of FDS and Cellular Automata

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Abstract: To investigate the influence of disaster factors such as temperature, smoke, and CO concentration on evacuation in fire scenarios, this paper establishes a fire evacuation model based on the dynamic coupling of Fire Dynamics Simulator (FDS) and cellular automata. The model maps FDS grids to cellular automata cells one-to-one, and uses Python and other technical means to load disaster data obtained from FDS simulations into cells in real time, enabling disaster data to continuously affect pedestrian transition probabilities and thereby achieving dynamic coupling between disasters and evacuation. Using a single-story teaching building as the simulation scenario, the model analyzes and discusses factors such as fire source location and heat release rate, revealing their influence patterns on pedestrian evacuation processes. The model is also compared with traditional software and similar approaches to identify similarities and differences. The research demonstrates that high temperatures and smoke from fires affect pedestrians' choices of evacuation paths and emergency exits. Higher heat release rates cause pedestrians to enter dangerous states earlier and increase the number of pedestrians in danger simultaneously. Compared with traditional evacuation software, this model not only considers the dynamic impact of fire-induced disaster factors on pedestrian evacuation but also determines the location and time when pedestrians first enter dangerous states, visualizing these outcomes.

Keywords: fire evacuation; FDS; cellular automata; dynamic coupling; simulation

0 Introduction

In recent years, building fires have occurred frequently, causing substantial casualties and property losses. According to statistics from the past decade, China has experienced 31,000 high-rise building fires, resulting in 474 deaths and direct economic losses of approximately 1.56 billion yuan [1]. During fires, psychological characteristics such as panic, herd mentality, and impulsiveness make it difficult for occupants to respond calmly and make rational escape decisions. Therefore, conducting research on pedestrian evacuation dynamics under fire conditions is essential to minimize fire-related casualties.

Given the dangers of fire conditions, conducting real fire evacuation experiments is impractical. Consequently, with advances in computer technology, computer simulation has become an important and feasible tool. Internationally developed pedestrian evacuation simulation software includes Pathfinder [2], Building EXODUS [3], and FDS+EVAC [4], which have high application value in engineering practice. However, these simulation software packages are based on fixed pedestrian evacuation models, and users cannot modify the actual movement rules—this represents their greatest limitation. For example, some scholars use

FDS to calculate the Available Safe Egress Time (ASET) for a building fire, then use Pathfinder to calculate the Required Safe Egress Time (RSET), and finally determine whether the building meets fire safety requirements by comparing RSET and ASET. This approach fails to adequately consider the impact of fire disaster factors on the evacuation process [1, 5].

For these reasons, increasing numbers of researchers have focused on developing evacuation models. Broadly speaking, evacuation models can be divided into macroscopic and microscopic models [6]. Macroscopic models treat crowd movement as fluid flow, enabling efficient calculation of evacuation times for large populations, but they are overly idealized and cannot reflect interactions and heterogeneity among individuals. In contrast, cellular automata models, as typical microscopic models, can reflect not only individual differences among pedestrians but also typical psychological characteristics and behavioral responses during evacuation, attracting widespread attention from researchers. Zheng et al. [7–9] improved the field-based cellular automaton model by considering the effects of fire and smoke on pedestrian movement and the influence of smoke layers on evacuation. Jin et al. [10] considered the impact of fire-induced panic psychology on pedestrian movement direction and proposed a cellular automaton evacuation model based on fire scenarios. Samuhar Polati et al. [11] defined pedestrian movement rules using quantified approach movement intensity and resolved conflicts during evacuation through a competitive point-occupation principle. Jiang et al. [12] constructed a fire evacuation model by analyzing existing cellular automaton theories and incorporating pedestrian evacuation characteristics, demonstrating that appropriate herd behavior improves evacuation efficiency in unfamiliar environments or emergencies. Chen et al. [13] proposed a field evacuation model considering the coupling effects of multi-exit attraction, herd behavior, and fire source threat to study the impact of fire sources on evacuation.

These studies show that many scholars have considered fire factors in pedestrian evacuation processes and established corresponding mathematical models. However, these models oversimplify and idealize flame spread and smoke diffusion [7–13], making it difficult to realistically reproduce evacuation processes in actual fires. Cao et al. [14] established a more realistic fire evacuation model by importing fire data into cellular automata through FDS, but their model still had simple scenario settings (without considering the impact of obstacle structures within building spaces on smoke diffusion and pedestrian evacuation) and low visualization capabilities. Therefore, this paper proposes a fire evacuation model based on the dynamic coupling of FDS and cellular automata.

1.1 Introduction to FDS and Cellular Automata

FDS is a fire simulation software with three-dimensional visualization capabilities. Based on a fire-driven fluid CFD model, it effectively describes low-Mach-number gas flow problems and accurately calculates temperature and gas concentration changes in fire scenes. It can compute smoke flow and heat transfer

processes while observing how parameters such as smoke, temperature, visibility, heat release rate, and combustion product concentrations vary during fires [15]. FDS establishes fundamental equations based on mass (species) conservation, momentum conservation, and energy conservation laws:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

$$\frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) + \nabla p = \rho \mathbf{g} + \mathbf{f} + \nabla \cdot \tau \quad (2)$$

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\rho h \mathbf{u}) = \frac{dp}{dt} + \dot{q}''' - \nabla \cdot \mathbf{q}'' + \Phi \quad (3)$$

$$p = \rho R T / W \quad (4)$$

where ρ is gas density (kg/m^3), \mathbf{u} is velocity vector (m/s), \mathbf{g} is gravitational acceleration (m/s^2), \mathbf{f} is external force vector (N), τ is Newtonian fluid viscous stress tensor (N), h is specific enthalpy (J/kg), p is pressure (Pa), \dot{q}''' is heat release rate per unit volume (W/m^3), \mathbf{q}'' is heat flux vector (W/m^2), T is temperature (K), Φ is dissipation function, R is ideal gas constant, and W is relative molecular mass of gas mixture.

Cellular automata originated from John von Neumann's Game of Life theory in 1951 and was applied to pedestrian evacuation research in public buildings in the 1980s. Unlike other kinetic models, cellular automata are not defined by strict physical equations or functions but by a series of construction rules. Cell states are updated in real time according to these rules and the states of neighboring cells, forming the evolution of a dynamic system. Common cellular spatial structures and neighborhood types are shown in Fig. 1 and Fig. 2, respectively.

1.2 Dynamic Coupling Model of FDS and Cellular Automata

FDS calculations of smoke flow and heat transfer are grid-based, enabling computation of disaster data (temperature, CO concentration, smoke concentration, etc.) for each grid at specific time intervals. Meanwhile, pedestrian movement in cellular automata evacuation models is also cell-based. Leveraging this correspondence, disaster data obtained from FDS are processed using Python and other data processing tools and loaded into cellular automata at the same time interval (time step) as evacuation updates. Real-time changing disaster data continuously affect the comprehensive field values in cellular automata, thereby influencing pedestrian movement transition probabilities in all directions. This achieves dynamic coupling between disaster data and evacuation behavior at each time step, as illustrated in Fig. 3.

It is noteworthy that disaster data from FDS exist in three-dimensional space, while pedestrian movement space in cellular automata is two-dimensional.

Therefore, data processing involves: (1) setting each FDS grid height to floor height; (2) selecting maximum values of temperature, smoke concentration, and CO concentration for each grid based on the most unfavorable principle of performance-based fire protection design; and (3) setting model time step update frequency to 1 step per 0.25 s, meaning disaster data are loaded and pedestrian positions updated every 0.25 s.

The fire evacuation model based on dynamic coupling of FDS and cellular automata is established on a two-dimensional grid with cell size set to 0.4×0.4 m (correspondingly, FDS grid plane size is also set to 0.4×0.4 m). Each cell is either empty or occupied by walls or pedestrians. Boundaries consist of walls and emergency exits; pedestrians reaching exits are considered successfully evacuated. Rectangular grids are selected as basic evacuation units, and Moore-type neighborhoods are used as pedestrian evacuation probability transition matrices to determine pedestrian movement direction. Pedestrian transition probability P_{ij} is given by:

$$P_{ij} = N \exp(k_S S_{ij} + k_D D_{ij} + k_C C_{ij} + k_T T_{ij})(1 - n_{ij})(1 - \varepsilon_{ij})$$

where N is a normalization factor ensuring $\sum_{ij} P_{ij} = 1$; i, j are target cell coordinates; $S_{ij}, D_{ij}, C_{ij}, T_{ij}$ represent static field, dynamic field, smoke field, and temperature field, respectively; and k_S, k_D, k_C, k_T are weight sensitivity coefficients reflecting the contribution of different fields to the total field, with $k_S, k_D, k_C, k_T \in [0, \infty)$. The terms n_{ij} and ε_{ij} represent occupancy information of other pedestrians and obstacles, respectively, calculated as:

$$n_{ij} = \begin{cases} 1, & \text{if target cell is occupied by wall or obstacle} \\ 0, & \text{if target cell is not occupied by wall or obstacle} \end{cases}$$

$$\varepsilon_{ij} = \begin{cases} 1, & \text{if target cell is occupied by pedestrian} \\ 0, & \text{if target cell is not occupied by pedestrian} \end{cases}$$

The static field S_{ij} represents the attraction of exits to pedestrians. Without obstacles, it can be calculated directly using distance formulas, but complex obstacles (e.g., U-shaped obstacles) may cause pedestrians to fall into local optima traps. The common solution is using Dijkstra's algorithm to calculate distances from each cell to exits; this approach is adopted in the obstacle-containing scenario of this study.

The model considers pedestrian danger states as follows: (a) Most smoke poisoning deaths are caused by CO; pedestrians are considered in danger when CO concentration in their cell reaches or exceeds 500 ppm [19]. (b) Extreme temperatures can also cause fatalities. According to existing research [17], humans cannot breathe in 65°C air, so 65°C is set as the critical temperature for floor

fire danger. In the model, pedestrians are in danger when the temperature field T_{ij} of their target cell is greater than or equal to 3.25.

Parameter values used in this study are shown in Table 1.

Table 1. Parameter values in this article

Parameter	Value
k_S	5
k_D	1
k_C	10
k_T	1

1.3 Evolution and Update Rules

The model employs parallel update rules to refresh all pedestrian positions simultaneously. The specific update rules are: (a) Initialize pedestrian distribution and calculate transition probabilities based on superimposed field strengths to determine next positions. (b) When multiple pedestrians compete for the same cell, one pedestrian is selected randomly with equal probability to enter the cell while others remain in place. (c) Identify pedestrians in danger states at each time step and mark them. (d) Update all pedestrian positions for the next time step and remove those at exit locations. (e) Repeat steps (a)–(e) until all pedestrians are evacuated.

The dynamic field D_{ij} describes herd behavior among pedestrians by referencing path information from other pedestrians, expressed as:

$$D_{ij}^{t+1} = (1 - \alpha)(1 - \delta)D_{ij}^t + \alpha \sum_{(i',j') \in \text{Neighborhood}} D_{i'j'}^t + \delta \Delta_{ij}^t$$

where α and δ are diffusion and decay coefficients, both set to 0.3 [16]. All cells have initial dynamic field values of 0. Whenever a pedestrian passes through a cell, the field value increases by 1. The terms d_1 and d_2 are correction coefficients: $d_1 = 1$ when cell (i, j) was empty in the previous time step and occupied in the current step, otherwise $d_1 = 0$; $d_2 = 1$ when cell (i, j) was occupied in both the previous and current time steps, otherwise $d_2 = 0$.

In real fire scenarios, smoke diffusion is faster and more severe than flame spread. Generally, other fire threats such as structural failure do not reach dangerous states before smoke does. Statistics show that 75%–85% of building fire deaths are caused by smoke [17]. The smoke field C_{ij} represents the repulsive effect of smoke concentration on pedestrians, with values directly exported from FDS. Notably, smoke concentration is inversely proportional to visibility, as shown in Eq. (12) [18]:

$$V = \frac{K}{C_m}$$

where V is visibility, K is an empirical constant, C_m is smoke particle mass concentration, and K is smoke particle extinction coefficient. Using the smoke field alone can represent the impact of smoke concentration on evacuation, so this model does not introduce the visibility field proposed in literature [14].

High temperatures from fires also pose serious threats to evacuation. Pedestrians instinctively move away from high-temperature areas toward cooler regions. Therefore, the temperature field T_{ij} represents temperature's repulsive effect, calculated as:

$$T_{ij} = \frac{T - T_0}{T_0}$$

where T is temperature data exported from FDS and imported into cellular automata via Python, and T_0 is ambient temperature (20°C).

2.1 Physical Environment Assumptions for Evacuation System

The evacuation simulation scenario is set as a 48.4×15.2 m single-story teaching building, with corresponding FDS grid and cellular space sizes of 121×86 grids (cells), as shown in Fig. 4(a) and 4(b). The floor height is 3.6 m. Two emergency exits are located on the left and right sides of the scenario, each 2.4 m wide. The classroom contains numerous desks and chairs. The fire heat release rate (HRR) follows an αt^2 growth pattern [20], and based on the most unfavorable principle, the fire growth type is set as fast fire with growth coefficient 0.04689, HRR of 5000 kW/m², and initial fire source area of 0.16 m². The fire source location is detailed in Fig. 4(a). In FDS, desk/chair material is set as “wood_{pine}” with combustion reaction “wood, soot yield ys=0.015 g/g and CO yield ys=0.004 g/g,” while walls, floors, and slabs are set as non-combustible inert materials. Black cells in the cellular automata scenario represent desks/chairs and walls, while green cells represent fixed-distribution pedestrians totaling 720 individuals. To reduce random errors, all evacuation time steps are averaged over 20 simulations.

In Pathfinder, “Steering” mode is selected with pedestrian shoulder width set to 0.4 m, behavior set to “Go to any exit,” and maximum speed of 1.6 m/s. The Pathfinder scenario is shown in Fig. 4(c).

2.3 Impact of Fire Source Location on Evacuation

To investigate the impact of fire source location on evacuation, comparative analysis is conducted across scenarios. Each scenario corresponds to one fire

source location while other parameters remain identical, as shown in Fig. 6. Fig. 7 displays the variation in evacuation numbers over time at left and right exits across three scenarios. Scenario 3 has the shortest total evacuation time, with pedestrians essentially evacuated by 160 time steps; Scenario 2 requires 200 time steps; Scenario 1 has the longest total evacuation time, with evacuation completed only at 260 time steps. These differences primarily result from varying exit utilization rates. When fire occurs in the middle position, pedestrians evacuate toward both sides, allowing both exits to be well utilized (the left and right exit curves in Scenario 3 are similar). As the fire source moves closer to the left exit, that exit becomes less safe, causing more pedestrians to choose the right exit and resulting in severe congestion there. For example, in Scenario 1, the left exit curve plateaus after 120 time steps while the right exit curve continues rising, indicating most pedestrians ultimately choose the right exit.

2.4 Impact of Heat Release Rate on Pedestrians in Danger

To explore how different heat release rates affect pedestrians entering dangerous states, three HRR values are compared in Scenario 1: (a) $\text{HRR} = 500 \text{ kW/m}^2$, (b) $\text{HRR} = 2000 \text{ kW/m}^2$, and (c) $\text{HRR} = 5000 \text{ kW/m}^2$. The maximum number of pedestrians in danger and the earliest time this occurs under different HRR values are shown in Fig. 8. Higher HRR causes pedestrians to enter dangerous states earlier and increases the number of pedestrians in danger simultaneously. This occurs because higher HRR leads to faster temperature rise and greater smoke production, preventing more pedestrians in classrooms near the left exit from evacuating promptly due to door width limitations.

Additionally, the model can visually represent pedestrians in danger at specific time steps. Fig. 9 shows pedestrians in danger at 40 time steps in Scenario 3 with $\text{HRR} = 5000 \text{ kW}$, where red cells represent pedestrians in dangerous states.

2.5 Comparison with Traditional Software and Similar Approaches

The Pathfinder simulation process at 120 time steps is shown in Fig. 10. Compared with Fig. 5(a), more pedestrians remain in the scenario at the same time step. The comparison of evacuation numbers over time between Pathfinder and this model (without fire) is shown in Fig. 11. This cellular automaton model uses Dijkstra's algorithm to calculate static fields, while Pathfinder's path planning is based on A* algorithm [21], which is essentially an extension of Dijkstra's algorithm [22]. Therefore, the difference likely arises because Pathfinder considers more pedestrian collisions and speed variations than cellular automata, as shown in Fig. 12.

However, Pathfinder's greatest limitation is its inability to consider fire's dynamic impact on evacuation. In Scenario 1 with $\text{HRR} = 5000 \text{ kW/m}^2$, traditional software safety assessment yields $\text{RSET} = 97.3 \text{ s}$ and $\text{ASET} = 56.7 \text{ s}$, with

RSET > ASET indicating unsafe evacuation, as shown in Table 2. This evaluation method simply runs two software packages separately and compares results without adequately considering fire's dynamic impact on evacuation paths and behaviors during development.

Although literature [12] also constructed a cellular automaton fire evacuation model considering fire source repulsion, its flame spread settings are overly idealized (random diffusion in Moore neighborhoods) and do not account for smoke diffusion and temperature effects on evacuation. In the proposed dynamic coupling model, fire-induced disaster factors influence pedestrian path and exit selection by affecting comprehensive field values. The model not only assesses evacuation safety but also determines the location and time when pedestrians first enter dangerous states, visualizing these results. Table 3 compares this model with literature [12].

Table 2. Evacuation safety evaluation results of traditional software

Disaster Time	ASET	RSET	Safety
Corridor visibility < 1.5 m	56.7 s	97.3 s	Danger
Smoke layer height			
Left exit temperature			
Right exit temperature			
Corridor CO concentration > 500 ppm	30.9 s		

Table 3. Model comparison between this paper and literature [12]

Feature	Literature [12] Model	This Model
Exit attraction	Introduced based on Dijkstra algorithm	Introduced based on Dijkstra algorithm
Herd behavior	Calculated based on pedestrian numbers in vision range	Referenced Kirchner A et al. [16] classic dynamic field
Fire repulsion	Introduced based on Euclidean distance	Comprehensive repulsion from temperature and smoke
Temperature repulsion	Not considered	Imported FDS data, introduced temperature field
Smoke repulsion	Not considered	Imported FDS data, introduced smoke field

Feature	Literature [12] Model	This Model
Danger state consideration	Rules for high temperature/high CO concentration	Visualization of flame spread, smoke diffusion, and dangerous states
Visualization	Visualization of flame spread only	Visualization of flame spread, smoke diffusion, and dangerous states

3 Conclusion

This paper provides a new method for studying pedestrian evacuation in fires by establishing a dynamic coupling model between FDS and cellular automata. The model can be applied to different building scenarios by varying parameters such as fire source location, combustible materials, heat release rate, and pedestrian density to identify the time when pedestrians enter dangerous states under most unfavorable conditions, thereby evaluating evacuation safety and providing references for performance-based fire protection design. The research demonstrates that: (a) fire-induced high temperatures and smoke affect exit selection, with pedestrians preferring paths and exits with lower temperatures and smoke concentrations as fires develop; (b) higher heat release rates cause pedestrians to enter dangerous states earlier and increase the number of pedestrians in danger simultaneously; and (c) compared with Pathfinder, this model considers the dynamic impact of fire-induced disaster factors on evacuation and can accurately determine the location and time when pedestrians enter dangerous states.

Future work based on this coupling model can incorporate previously proposed behaviors such as crawling and consider fire-induced pedestrian panic psychology. Additionally, modeling and analysis of multi-story building fire evacuation can be further developed, along with incorporating pedestrian pre-movement times and fire protection systems such as automatic sprinkler systems.

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