Design and Implementation of Fire Safety Evacuation Simulation Software based on Cellular Automata Model

Yi Yang\textsuperscript{a,b,*}, Jun Deng\textsuperscript{a}, Chang-chun Xie\textsuperscript{a}, Yun-tao Jiang\textsuperscript{c}

\textsuperscript{*}Key Laboratory of Western Mine Exploitation and Hazard Prevention of Ministry of Education, Xi’an University of Science and Technology, Xi’an 710054, China

\textsuperscript{b}Xi’an Public Security Fire Detachment, Xi’an 710065, China

\textsuperscript{c}Department of fire protection engineering, Chinese People’s Armed Police Force Academy, Langfang 065000, China

Abstract

A fire evacuation model was developed based on cellular automata (CA) to simulate occupant evacuation behaviors in case of public place fires, which can reflect individual characteristics, herd behaviors and the environmental effects on the evacuation behavior. The fire safety evacuation simulation software based on the model was programmed by c# language on the platform of Microsoft Visual Studio 2008. The occupant evacuation process in fire scenario was displayed through the software, and the simulation came with the same result with actual situation. This software, with intuitive, flexible and extendable, has realized the anticipated functions, such as generating fire scenario, simulating evacuation behaviors and managing legal norms of fire safety. Furthermore, it provides a platform for further research on fire safety evacuation in public places.

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Keywords: occupant evacuation simulation, cellular automata, software design, public place fire

Nomenclature

\begin{align*}
P_g & : \text{grid attraction index} \\
P_{\text{decide}} & : \text{decide attraction index} \\
P_{\text{follow}} & : \text{follow attraction index} \\
FP & : \text{avoiding fire attraction index} \\
PP & : \text{exit attraction index} \\
K_{\text{guide}} & : \text{guide signs attraction index} \\
(s, a) & : \text{age and gender attribute} \\
Competitiveness & : \text{competitive attribute} \\
\text{Greek symbols & Coefficients} & \\
\alpha & : \text{avoiding fire attraction coefficient} \\
\beta & : \text{exit attraction coefficient} \\
\gamma & : \text{guide signs attraction coefficient} \\
k_1 & : \text{decide attraction coefficient} \\
k_2 & : \text{follow attraction coefficient} \\
\text{Subscripts} & \\
t & : \text{at the } n\text{th time step}
\end{align*}

* Corresponding author. Tel.: +86 – 13309229593.
E-mail address: yangyi_610@163.com

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doi:10.1016/j.proeng.2014.04.052
1. Introduction

In recent years, there is a growing concern over the problem of fire safety evacuation, because of a large number of casualties caused by fire accident in some large public places [1]. During some emergency circumstances, as fire or earthquake, the priority of people is to make their life and property safe, so that successful escape is one of the most important measures [2]. Consequently, it is very significant to assess the evacuation capacity of such public places and describe the behaviors of occupant evacuation.

At present, the foreign scholars have developed more than 20 evacuation models to solve the evacuation problems [3-8]. Most of them ignored the influences of individual subjective consciousness and information obtained from evacuation behaviors, so that the simulation results slightly differ from the real situation. Much more complicated behaviors can be considered by using Cellular Automata (CA) model. It reflects the individual characteristics, individual’s psychological response in disasters, interaction between individuals, as well as the influence of structure and environment on the evacuation behaviors. Recently, CA model has become a frontier research field at home and abroad [9-11].

Because of the pressing demand for solving the issue of occupant evacuation, it is need to develop fire safety evacuation software by constructing a CA model [12]. At this time, this software can not only simulate the evacuation behavior patterns around emergency environment, but also assess the evacuation capacity of such public places.

2. Demand analysis and outline design

2.1. Customer requirement analysis

Fire workers and researchers will be main users of this software. Therefore, the simulation of the software should resemble the real circumstance, which helps the users to research the problems facing in emergency evacuation. Besides, a database should be established to arrange the regulations and standards of fire safety evacuation, so that our users can check and print the legal norms by it.

2.2. Functional module design

According to the needs of research and application, six main functional modules were designed, including layout module, occupant module, background calculating module, simulation displaying module, legal norms management module, algorithm management module (see Fig. 1).

![Fig. 1. the software functional modules](image)

2.3. Database design

The main function of the software is to simulate the evacuation process, while database management is just an auxiliary function, mainly used to manage legal norms of fire safe and software algorithms. The concept structures of database were designed considering above description. The entity of database includes two parts: the legal norms entity (number, release date, name, content, note); the software algorithm entity (number, name, content, note).
According to the results of conceptual design, the logic structures of data tables were designed, showing in Table 1 and Table 2.

Table 1. logic structure of legal norms entity

<table>
<thead>
<tr>
<th>Name</th>
<th>Data Types</th>
<th>Mandatory Fields</th>
<th>Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>nvarchar(50)</td>
<td>yes</td>
<td>clauses No.</td>
</tr>
<tr>
<td>promulgation time</td>
<td>nvarchar(50)</td>
<td>no</td>
<td>promulgation time of clauses</td>
</tr>
<tr>
<td>Name</td>
<td>nvarchar(50)</td>
<td>no</td>
<td>name of clauses</td>
</tr>
<tr>
<td>Content</td>
<td>text</td>
<td>no</td>
<td>content of clauses</td>
</tr>
<tr>
<td>Note</td>
<td>text</td>
<td>no</td>
<td>note</td>
</tr>
</tbody>
</table>

Table 2. logic structure of software algorithm entity

<table>
<thead>
<tr>
<th>Name</th>
<th>Data Types</th>
<th>Mandatory Fields</th>
<th>Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>int</td>
<td>yes</td>
<td>algorithm No.</td>
</tr>
<tr>
<td>Name</td>
<td>nchar(10)</td>
<td>no</td>
<td>name of algorithm</td>
</tr>
<tr>
<td>Content</td>
<td>text</td>
<td>no</td>
<td>content of algorithm</td>
</tr>
<tr>
<td>Note</td>
<td>text</td>
<td>no</td>
<td>note</td>
</tr>
</tbody>
</table>

2.4. Application platform and model selection

The software was programmed on the Visual Studio 2008 software development platform, using object-oriented C# language, and embedding SQL Server 2005 database management tools to manage legal norms of fire safety and software algorithm. It has some advantages due to this structure, which are object-oriented program, efficient development, stable operation, powerful function, and so on.

Pedestrian flow model based on CA is simple and able to reproduce various complex phenomenon of pedestrian flow with characteristics of time discreteness, spatial discreteness and calculating synchronization [13]. Therefore, CA theory was adopted to establish occupant evacuation model in fire scenario.

3. Constructing occupant evacuation model based on cellular Automata

3.1. Attributes of object

3.1.1 Attributes of grid

(1) Defining space and neighbors

A public place was looked as a cellular space, as Fig. 2. Spatial coordinates can be expressed by grid discrete coordinates \((i, j)\), \(i=0, 1, \ldots, a; j=0, 1, \ldots, b\). Grid size, based on body size, is \(0.55m \times 0.55m\).

Moore type neighborhood was adopted to establish the model [14]. If person’s position changes, eight neighbors grid can be chose.

![Cellular space and Moore type neighborhood](image)

In the cellular space, every point has only one status \(K_{\text{cell}}\), which was defined in formulas (1).
(2) Grid attraction index: \( P_{ij} \)

Grid attraction index \( P_{ij} \) is an important indicator for occupants to choose the direction of motion at the next time step [15]. According to the set moving direction and visual field (see Fig. 3), nine of grid attraction index \( P_{ij} \) —including former position and 8 neighbors—are calculated and compared to determine the moving direction, and then update the occupant positions at the next time step.

Grid attraction index \( P_{ij} \) consists of decide attraction index \( P_{\text{decide}} \) and follow attraction index \( P_{\text{follow}} \). \( P_{\text{decide}} \) is determined by avoiding fire attraction index \( FP \), exit attraction index \( PP \) and guide signs attraction index \( K_{\text{guide}} \). \( P_{\text{follow}} \) depends on the population density and moving direction in 8 neighbor areas of visual field, see the following formula (2) ~ (5).

\[
P_{ij} = k_1 \cdot P_{\text{decide}} + k_2 \cdot P_{\text{follow}}
\]

\[
FP = \frac{(i-i_{\text{min}})^2 + (j-j_{\text{min}})^2}{\sqrt{(i_{\text{fire}}-i_{\text{min}})^2 + (j_{\text{fire}}-j_{\text{min}})^2}}
\]

\[
PP = 1 - \frac{(i-i_{\text{min}})^2 + (j-j_{\text{min}})^2}{\sqrt{a^2 + b^2}}
\]

Assume \( k_1, k_2, \alpha, \beta, \gamma \) are coefficients. And \( k_1+k_2=1, \ 0\leq k_1, \ k_2\leq 1; \ \alpha+\beta+\gamma=1, \ 0\leq\alpha,\beta\leq 1 \). If someone see and follow the guide signs, \( \gamma=1 \); if not, \( \gamma=0 \). Diagonal dimension of cellular space is \( \sqrt{a^2 + b^2} \). Center’s coordinates of fire source is expressed as \((i_{\text{fire}}, j_{\text{fire}})\), which value should be set before simulation. \((i_{\text{farfire}}, j_{\text{farfire}})\) is the furthest position away from fire in cellular space, which is the maximum of all distances calculating from all the coordinate points to fire source center. \((i_{\text{exitmin}}, j_{\text{exitmin}})\) is the position of the nearest exit, which is the minimum of all distances calculating from the \((i, j)\) to all the exits. \( N_n \) is the number of people who ran to the \( n \)th direction in the visual field at the \( n \)th time step \((n=1, 2...8)\).

(3) The scope of fire

When the fire breaks out, fire source will occupy a certain area, at the same time, the thermal radiation zone around the fire is considered to be inaccessible. At the beginning of simulation, the range of \( r \leq 3 \) is taken as thermal radiation area (see Fig. 4). \( r \) is the number of squares from regional boundary to the center of fire.

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**Fig. 3. Setting moving direction and visual field**

**Fig. 4. fire source and thermal radiation zone**
3.1.2 Attributes of occupant

After occupant determine the target square, they can only enter the target square when their attributes are corresponding with some specific requirements. Otherwise, they should stay in situ at this time step.

(1) Age and gender attribute: \((\text{sex}, \text{age})\)

The age and gender attribute \((\text{sex}, \text{age})\) is given to each person, which value is shown in formulas (6) and (7). During initialization, age and gender attributes of occupant are evenly distributed by system. Each person takes \((\text{sex}, \text{age})\) to quantify the attributes of age and gender.

\[
\text{sex} = \begin{cases} 
1, & \text{men} \\
0, & \text{women} 
\end{cases} \tag{6}
\]

\[
\text{age} = \begin{cases} 
1, & \text{middle-aged (from 40 to 60)} \\
2, & \text{young (before 40)} \\
0, & \text{old (older than 60)} 
\end{cases} \tag{7}
\]

(2) Competitive attributes: \(\text{competitiveness}\)

When a target grid has more than one candidate, it needs to identify each one’s competitive attribute \((\text{competitiveness})\) according to age and gender attributes. The one with maximum of \(\text{competitiveness}\) will enter the target square. It was assumed that the size relation of person’s \(\text{competitiveness}\) was: young men > middle-aged men > young women > middle-aged women > old men > old women. Person’s \(\text{competitiveness}\) was separately assigned by 6, 5, 4, 3, 2, 1, as shown in formula (8).

\[
\text{competitiveness} = \begin{cases} 
6, & \text{while } (\text{sex}, \text{age}) = (1, 2) \\
5, & \text{while } (\text{sex}, \text{age}) = (1, 1) \\
4, & \text{while } (\text{sex}, \text{age}) = (0, 2) \\
3, & \text{while } (\text{sex}, \text{age}) = (0, 1) \\
2, & \text{while } (\text{sex}, \text{age}) = (1, 0) \\
1, & \text{while } (\text{sex}, \text{age}) = (0, 0) 
\end{cases} \tag{8}
\]

(3) Position attributes

At the \(t\) time step, the coordinates of person and neighbor are shown as Fig. 5.

\[
\begin{array}{ccc}
(i_{t-1}, j_{t+1}) & (i_n, j_{t+1}) & (i_{t+1}, j_{t+1}) \\
(i_{t-1}, j_t) & (i_n, j_t) & (i_{t+1}, j_t) \\
(i_{t-1}, j_{t-1}) & (i_n, j_{t-1}) & (i_{t+1}, j_{t-1}) \\
\end{array}
\]

Fig. 5. neighbor grid coordinates at time \(t\)

A target grid matrix was set up according to neighbor grid coordinates and the corresponding grid attraction index. The attraction index of neighbor grid which is occupied by obstacle or person is assumed as zero.

\[
\begin{bmatrix}
(i_n, j_{t+1}) & (i_{t+1}, j_{t+1}) & \cdots & (i_{t-1}, j_{t+1}) \\
P_1 & P_2 & \cdots & P_n
\end{bmatrix}
\]

At the \(t+1\) time step, the coordinate of target grid was set as \((i_{t+1}, j_{t+1})\). The coordinate of target grid, which is the maximum of \(P_{ij}\) (grid attraction index), is recorded into \((i_{t+1}, j_{t+1})\). Then the coordinates \((i_n, j_t)\) and \((i_{t+1}, j_{t+1})\) are saved.

3.2. Occupant evacuation process during public place fires

The update process of occupant position is shown as Fig. 6. At first, everyone’s location \((i, j)\) and \(\text{competitiveness}\) are recorded. And then, the free neighbor grids’ attraction index \((P_0)\) are calculated to choose the maximum as the target grid \((i_{t+1}, j_{t+1})\) coordinate at the \(t+1\) time step. When the same target grid correspond with more than one person, comparing each one’s \(\text{competitiveness}\), the maximum value of the person could enter the target grid \((i_{t+1}, j_{t+1})\), others stay in situ. When there are more than two maximum values of the personal \(\text{competitiveness}\), only one can enter the target grid by randomly selected with the same probability and the rest stay in situ. To simplify the model, personal moving average velocity takes as 1.2m/s to calculate the evacuation time of occupant.
4. Software testing and model validation

4.1. Software testing

During the software testing, the related parameters were set as follows:

(1) The overall dimensions
The size of a grid was set as \(0.55 \times 0.55\) m, and this area was divided into \(60 \times 60\) grids. According to above parameters, the actual area of the places could be calculated as \(33\times 33=1089\) m\(^2\).

(2) Exit location and width
According to GB50016-2006 "Code of Design on Building Fire Protection and Prevention", the minimal setting requirements of emergency exit is: Emergency exits in this place should be not less than 2 at least; clear width of each exit should be not less than 2m at least, and the total width should be not less than 4m; separation distance of exits should be not less than 10m. However, people usually choose the coming escape route while in a strange environment, so that the entrance is often the exit what they choose when they are evacuating. The public place chosen in this model was a large space, with wide exits. So when setting evacuation scenario, the width of exit was set as 10m, that was, 18 grids. The coordinates of central point of exits were (18, 0) and (44, 0).

(3) The number of evacuating people
According to GB50016-2006, each person’s usable area shall not less than 1.1m\(^2\), therefore, the person’s usable area was set as \(2\) m\(^2\), and the population density was 0.5 people/m\(^2\). It was obtained from the above setting that the number of people for evacuation maximized to 500. Assuming the number of people in the area as 500, System distributed occupant according to the average ratio of the age and gender attributes randomly.

(4) Fire source's position
The coordinate of fire source’s position was set as (30, 30), and the range of \(r\leq 3\) around the fire was the thermal radiation area that people cannot enter.

(5) Personal moving velocity
When the occupant density is less than 0.5 people/m\(^2\), person moves at the velocity of 1.2m/s. The moving velocity decreases with the density increasing, and when the density reaches 4 or 5 people/ m\(^2\), people almost cannot move. Here we set the occupant density as 0.5 people/ m\(^2\), so the average moving velocity of people was set as \(v_0 = 1.2\) m/s.

(6) Set the coefficients of formulas
After many experiments, when the ratio of alpha and beta was about 1:9, simulation effect was the best. Otherwise, it was possible for people to move away from exits or move in circles to escape from fire, which all didn’t accord with actual situation. Therefore, avoiding fire attraction index coefficient was \(\alpha=10\%\), decide attraction was \(\beta=50\%\). The possibility coefficient \(\gamma\) of guided by indication evacuation in the guide area was set as 50%. Determination coefficient was \(k_1=95\%\), follow coefficient was \(k_2=5\%\). Assumed the fire point coordinate as (30, 30), a place with the boundary wall generated on the interface and showed the fire area.

10 times of simulation experiments had been carried out (see Fig. 7), and the results was shown in Table 3.
As mentioned before, the size of a grid was 0.55 m × 0.55 m, and $v_0 = 1.2$ m/s. So, time per step $t_0 = 0.55 / 1.2 = 0.46$ s.

According to Table 3, an average of time step: $\bar{n} = (n_1 + n_2 + \cdots + n_{10}) / 10 = (188 + 198 + \cdots + 201) / 10 = 196.6 \approx 197$

Then, an average of evacuation time: $\bar{t} = (t_1 + t_2 + \cdots + t_{10}) / 10 = 90.109$

So, the average of evacuation time was about 90 s.

Standard deviation ($S$) was inacceptable range: $S = \sqrt{\frac{1}{10}((\bar{t} - t_1)^2 + (\bar{t} - t_2)^2 + \cdots + (\bar{t} - t_{10})^2)} = 3.65$

4.2. Comparing the simulation results and empirical formula

To verify the simulation results by empirical formula based on “Speed - flow - density”, which is often used in Fire evacuation calculation.
In this formula: $f_0$ is the outlet flow; $v_0$ is average walking velocity; $s_0$ is population density; $w_0$ is effective width of exit; $t$ is the overall evacuation time; $N$ is the total number of evacuation.

If $v_0=1.2$ m/s, $s_0=500/1089=0.46$ people/m², $w_0=0.55\times18=9.9$ m, and $N=500$ people. Then, the flow rate of the exit: $f_0 = 1.2\times0.46\times9.9 = 5.46$ people/m². So, the overall evacuation time: $t=500/5.46=91.49$ s.

By simulation, the average of evacuation time was 90.109 s, which was approximate to the calculation results by empirical formula. Consequently, the model for simulation of evacuation process has certain reliability and advantage.

5. Conclusion

(1) The evacuation CA model was established and improved, based on analyzing the personal decision-making process and the movement pattern in congested condition when the occupant were escaping from fire scene. It also contained various factors influencing the choice of evacuation direction, such as direction of fire avoiding, exit location, guide signs, herd behavior, competitiveness of personal attributes, etc. Consequently, this model can describe the movement process of occupant in detail.

(2) Visual fire safety evacuation simulation software was developed to imitate the process of occupant escaping from the fire in public places by embedding the CA model. This software has achieved the anticipated functions, such as generating different fire scenarios in public places, dynamic simulating evacuation behavior and managing legal norms of fire safety. As a result, researchers can visually observe the tendency and regular pattern of personal movement in the case of fire with it.

In conclusion, by doing this, the software developed in this project can better satisfy fire safety evacuation researchers’ requirements in application. It will provide a platform for researchers to study occupant evacuation in a specific fire scene.

References