GIS Based Dynamic Modeling of Fire Spread With Cellular Automation Model

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Abstract: **This paper presents a GIS based dynamic modeling of fire spread using cellular automation simulation, given a set of stochastic ignition points and initial environmental settings. Modeling every individual room in the building as a cell, we have developed the algorithm for fire spread both from room to room inside a building and from one building to another due to radiation and branding. The models perform in the cellular automation programming and the results are intended to be dynamically visualized in a Geographic Information System (GIS) that include data of digital elevation model, 3D building models and environmental settings, such as temperature, wind direction and velocity.**

Keywords: fire spread; disaster modeling; GIS; cellular automation; emergency management; disaster management

I. INTRODUCTION

Fire hazards that spread in one building and among buildings are serious disasters. The fatalities, though occurring occasionally, threaten our lives and cause significant property losses. In history, there have been some fire disasters of great magnitude, who are usually led by battlefields and earthquakes. For instance, the second-world-war has brought huge fire disasters in Hamburg (1943) and Hiroshima (1945) [1-2]. Another example is the wide spread fire in San Francisco (1906), which covers over 521 blocks and damages over 508 blocks [3]. These instances illustrate the great damaging power of the widely spreading fire, and in front of which, our human beings are too weak to challenge. With the rapid development of urbanization, the size of our cities are getting bigger and bigger and the combustible materials are accumulating to a critical volume, which put us into great dangers of fire hazards.

Different from fire spread in forests, fire spread among buildings has its unique properties. A large amount of scholars around the world have investigated this process seriously. So far, the models of fire spread among buildings can be summarized into 3 categories, namely empirical models, probability models and physical models [4]. Empirical models are mainly developed by Japanese researchers. They have generalized empirical formulas according to historical data. Probability models adopted mathematical equations to describe the stochastic process of the fire spread among buildings. This method matches the indefinite nature of fire spread, however, fails to demonstrate the physical principle of the fire spreading [5]. Physical models are based on the fire spread rules, including the physical substances and energy laws. They are more related to the real process the fire happens and spreads. And numerous scholars have established plenty of models based on physical approaches.

Cellular Automation Model, which is capable of describing a dynamic system in discrete time and space, is also used broadly in simulating fire spreading process. Cells, who are the fundamental operating units of the model, are scattered in Lattice Grid. They are subjected to the same rules of preforming and are updated the status together in every time step according to the boundary conditions of the cells [6]. In Cellular Automation Model, there is no macro equations to cover the whole system. Every cell intends to calculate its own values and according to which justify its status. Traditional fire spread modeling with Cellular Automation Model neglected the physical properties of the fire transmission and fails to make an accurate outcome of the simulation [7]. Thanks to contributions of other researchers [8], we are now capable of integrating the physical characters into Cellular Automation Model to model the fire spread process, and which enables us to take advantages of the both models.

GIS is an interdisciplinary subject [9], which is based on informatics science, geospatial science and earth science. In recent years, GIS is largely used in assessing, simulating and forecasting the natural disasters and emergency management platforms. To simulate and visualize the fire spread process here, GIS is certainly the best choice, because GIS can organize and archive information relative to architecture layout and space analysis. Furthermore, GIS has powerful movie visualization functions, which can enhance the visibility of the simulation of the fire spread process.

In this paper, a GIS based dynamic modeling of fire spread with cellular automation model is proposed. Models for fire spread within a building, fire spread among buildings and branding are included to support the modeling. Meanwhile, we have adopted GIS method to analyze and visualize the whole process.

This paper is organized as follows. Section 2 presents the modeling of fire spread within a building. Section 3 introduces the modeling of fire spread among buildings. Section 4 describes an experimental setting and shows the discussions. Section 5 concludes the paper.

II. THE MODELING OF FIRE SPREAD WITHIN A BUILDING

Modeling fire from rooms to rooms within a building is the foundation of our work, since modeling the fire from one building to another due to radiation is actually the process of

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fire spread from rooms of one building to rooms in another building. Adjacent rooms may be ignited by neighbors in fully developed fire status through doorways and rooms above could be influenced by windows. For the fire spread modeling within a building, we consider conditions of fire spread in both horizontal and vertical directions. While probabilistic methods are taken advantage of to describe the status of the cells in compartments and the barrier failure in the fire spread modeling of horizontal directions inside a building, wind direction and velocity, which are critical to fire spread in vertical directions [10], are carefully considered in our model.

In our dynamic fire spread modeling, cellular automation model is mainly adopted to simulate the fire spreading process, due to its ideal property of finite status and transfer capability in the dimensions of time and space. In our case, we denote each compartment (room) as one cell, which has the status of dormant (before ignition), growth (before flashover), fully developed fire (before decay) and decay (before extinguishment), to form the basic elements of the model.

A. Fire Spread Within A Building Through Horizontal Directions

According to the hypothesis above, each compartment (room) is represented as a cell in Cellular Automation Model. When the fire is spreading in a floor, the ignition of neighbor rooms within a time step is dependent on two factors, the current burning room at the state of fully developed and the barrier failure between the burning rooms and the non-burning rooms. Only when the current room is at the state of fully developed and the barriers (mainly closed doors) between rooms fails, the neighboring non-burning rooms can be ignited in the next time step by fire flames.

When a room is ignited, the duration from ignition to flashover is determined by (1) [11]:

$$t = \sqrt{\frac{750 A_0 \sqrt{H_0}}{\alpha}} \quad (1)$$

Where t is the time of the growth phase, from ignition to flashover, in a compartment; A_0 is the area of the ventilation opening; H_0 is the height of the ventilation opening; α is the growth coefficient and the empirical value of α is shown in Table I.

TABLE I. FIRE GROWTH PARAMETER.

Fire Growth Rate	**Fire Growth Parameter α**	**Time (s)**
Slow	0.0029	600
Medium	0.012	300
Fast	0.047	150
Ultra-fast	0.188	75

Another factor influencing the fire spread in a floor is the barrier failure. We assume that the barrier failure is subject to normal distribution [12]. Thus the density function of barrier failure is described by (2) [12]:

$$P_{bf}(t) = \frac{1}{\sigma_{bf}\sqrt{2\pi}} \exp(-[(t-t_0)-\mu_{bf}]^2 / 2\sigma_{bf}^2) \quad (2)$$

Then the probability of the barrier failure is represented by (3) [12]:

$$P_{bf}(t) = \int_{t_{f0}}^{t} \frac{1}{\sigma_{bf}\sqrt{2\pi}} \exp(-[(t-t_{f0})-\mu_{bf}]^2 / 2\sigma_{bf}^2) dt (0 \le t - t_{f0} \le \tau_{fd}) \quad (3)$$

According to the fire safety design, the mean fire-resistance duration μ_{bf} and the deviation σ_{bf} can be known from ISO 834 standard [18]. Note that doors are the main barrier in the building and wood is the typical materials of doors here in China. Therefore, according to ISO 834 standard, the mean fire resistance duration is 10 minutes and the standard deviation is 1.5 minutes.

B. Fire Spread Within A Building Through Vertical Directions

Besides the two pre-conditions, current burning room in the fully developed status and barrier failure, fire spread through vertical directions should meet the wind velocity criteria. According to H.X. Chen etc. [13], in order to transmit the fire flame, wind velocity must reach a critical value, which is described in (4):

$$V > \sqrt{2(1-\frac{T_0}{T_g}) gH / (C_{p,W} - C_{p,L})} \quad (4)$$

In (4), T_0 is the ambient temperature; T_g is the burning room's temperature; $C_{p,w}$ and $C_{p,L}$ are, respectively, the pressure coefficients of windward side and leeward side.

III. THE MODELING OF FIRE SPREAD AMONG BUILDINGS

Radiation ejected out from burning rooms by gas and flames fluxed through windows. The received radiation of a room in another building is the sum of heat absolved from all the facing rooms. To figure out the total radiation, the configuration factor (or view factor), which is used to estimate of the fraction of the heat transferring from rooms in one building to rooms in other buildings, is of great importance [14]. In our model, we have carefully calculated the configuration factor and apply the theory to the calculation of the radiation transferring from burning rooms to other non-burning rooms. Besides radiation, branding is also another significant way to transmit fire. And we will describe in this section in turn.

A. The Configuration Factor

The configuration factor, or view factor, is a parameter describing the radiative heat transfer process. It stands for the proportion of the radiation which leaves surface A that strikes surface B [15]. And (5) describes the calculation of the configuration factor from surface A to surface B [15]:

$$F_{1\to 2} = \frac{1}{A_1} \int_{A_1} \int_{A_2} \frac{\cos\theta_1 \cos\theta_2}{\pi s^2} dA_2 dA_1 \quad (5)$$

Where θ_1 and θ_2 are the angle between a ray between the two differential areas and the surface V-perpendicular line [15]; s is the length of the ray.

B. Fire Spread Among Buildings Due To Radiation

Burning rooms ejected radiation via gas and flame. And the radiation received by the target room is the sum of the energy emitted from multiple sources. According to the data in Quintiere (2006), the empirical relationship between summed heat received and the ignition delay is shown in Table 2 [16].

TABLE II. RELATIONSHIP BETWEEN RADIATION AND IGNITION DELAY

Radiation (kW/m^2)	Time delay until ignition (min)
12.5	30
15	25
17.5	10
20	7
30+	1

In our settings, we assume the duration of each time step is 5 minutes, then according to the data in the Table II, the total radiation received from multiple sources should be above 20kW/m^2. Window flames and room gas are the two main source of radiation that should be calculated separately. The radiation transferred from window flames and room gas respectively is described in (6) and (7)[14]:

$$I_z = \phi_z \varepsilon_z \sigma (T_z^4 - T_a^4) \tag{6}$$

$$I_f = \phi_f \varepsilon_f \sigma (T_f^4 - T_a^4) \tag{7}$$

where T_f, T_z and T_a are the temperatures of room, flame and ambient respectively; ε_f and ε_z stands for the emissivity of the room gas and flame; σ is the Stefan-Boltzmann constant.

C. Fire Spread Among Buildings Due To Branding

Branding is another significant factor of fire spread, which usually occurs at the latter phase of the fire [17]. It can cause ignition points far away by carrying the burning sphere-like grains by wind from the current fire spreading areas. In our simulation, probabilistic methods are used to calculate this stochastic process with the variation of wind direction and strength, fire brand size and empirical data.

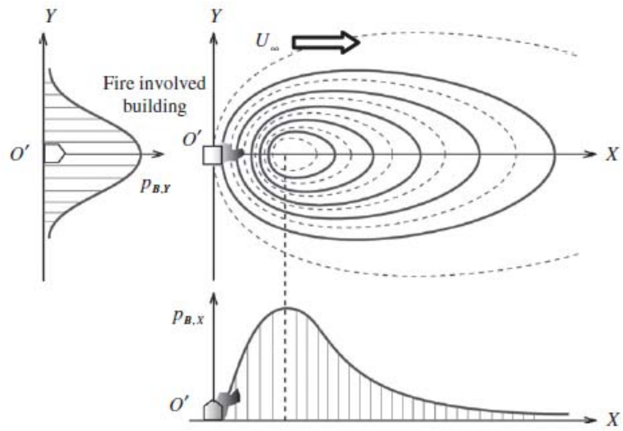

Figure 1. Himoto and Tanaka's probabilistic brand transport model [17]

Figure 1 describes the stochastic process of the firebrand scattering emitted from a burning building [17]. X axis stands for the wind direction, whereas the Y axis points to the orthogonal direction of the wind direction. A log-normal distribution P_x is described as the distribution of the firebrand along wind direction; whereas a normal distribution P_y is described as the distribution of the firebrand along the orthogonal direction of the wind direction. And they can be calculated by (8) and (9).

$$P_X = \frac{1}{\sqrt{2\pi}\sigma_X X} \exp\{-\frac{(\ln X - \mu_X)^2}{2\sigma_X^2}\} \tag{8}$$

$$P_Y = \frac{1}{\sqrt{2\pi}\sigma_Y} \exp\{-\frac{Y^2}{2\sigma_Y^2}\} \tag{9}$$

where μ_X is the mean of logarithm natural of the transport distance $\ln X$; σ_X and σ_Y are the standard deviation along X axis and Y axis respectively.

IV. Experiment Settings And Discussion

A. Study Area

As shown in Figure 2, we take the landscape and the dormitory buildings in Tsinghua Campus, University Town of Shenzhen to simulate the fire spreading process.

Figure 2. An example of the environmental settings (the landscape and the dormitory buildings)

B. Discussion

The dynamic fire spreading process is simulated and shown in GIS-based platforms. The rooms' placement in a building is generated artificially from remote sensing data and which may not stand for the real case. With the change of the value of the variations, the simulation process is adapted and the results are adjusted with the new alternation of inputs. The cellular status and barrier failure rates should not be identical in every simulation since they are based on the stochastic equations and the same happens to ignition points caused by branding.

As shown in Figure 3, the ignition point starts from a room in the 5th floor of one dormitory building. As time goes by, the fire spread process begins from the horizontal direction within the floor of that building to the vertical direction. Then the students dining hall, the building just in the face of the burning rooms, is ignited due to radiation heat transferring from the burning dormitory building.

Figure 3. An example of the fire spread process

The entire simulation of the fire spread process in this scenario is still in progress, and the data are still incomplete. In the future, the model needs to be verified through the real data from the experiment, and the heterogeneous cells model is to be conducted to enhance the performance.

V. CONCLUSIONS

In our work, we have developed the mathematical models of fire spread within and among buildings with the cellular automation methods, as well as establishing a 3D GIS based platform to simulate and visualize fire spread in a university town area. Each compartment is viewed as a cellular working unit and dynamic probabilistic models and physical laws are applied to support the calculation of fire spreading. In the future, we intend to complete the fire spread models in our GIS platform and promote our model with heterogeneous cells model that should be capable of simulating more complicated room structures which are more resemble to the real case. The proposed model certainly is able to be applied in different landscape with different building deployment and different environmental inputs, such as the built-up areas in the city.

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