GIS Based Dynamic Modeling of Fire Spread with Heterogeneous Cellular Automation Model and Standardized Emergency Management Protocol

Zhanghua Li
Institute of Safety Science and Technology (Shenzhen), Shenzhen Graduate School，Tsinghua University, Shenzhen 518055, China
zh-li15@mails.tsinghua.edu.cn

Fei Wang*
Institute of Safety Science and Technology (Shenzhen), Shenzhen Graduate School，Tsinghua University, Shenzhen 518055, China
wang.fei@sz.tsinghua.edu.cn

Xiaocui Zheng
Institute of Safety Science and Technology (Shenzhen), Shenzhen Graduate School，Tsinghua University, Shenzhen 518055, China
zheng.xiaocui@sz.tsinghua.edu.cn

Wenyu Jiang
School of Remote sensing and Information Engineering, Wuhan University, Wuhan 430079, China
2014302590164@whu.edu.cn

Qingxiang Meng
School of Remote sensing and Information Engineering, Wuhan University, Wuhan 430079, China
mqx@whu.edu.cn

Binbin Liu
Institute of Safety Science and Technology (Shenzhen), Shenzhen Graduate School，Tsinghua University, Shenzhen 518055, China
liubb16@ mails.tsinghua.edu.cn

ABSTRACT

This paper presents a GIS based dynamic model of fire spread using heterogeneous cellular automation simulation, given a set of stochastic ignition points and initial environmental settings. Modeling forests and concrete buildings in different types of cells, we have developed the algorithm for fire spread in hybrid urban scenario. As a consequence, our method can model the fire spread process of fire spread from forest areas to urban areas and vice versa in a single experiment. The model is built upon B-S standardized emergency management protocols, which we have customized from the Web Processing Service (WPS). And the standardized emergency management protocols can manage a set of different disaster models in a common structure. The structure of the simulation platform is established to dynamically visualize the fire spread process. And a comparison of experimental results with different wind velocity is carried out to illustrate the model.

*Corresponding to wang.fei@sz.tsinghua.edu.cn

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CCS CONCEPTS

• **Computing methodologies** → Modeling methodologies
• **Information systems** → Geographic information systems

KEYWORDS

Fire spread model; emergency management; GIS; heterogeneous cellular automation; standardization

1 INTRODUCTION

Different from wildfire, fire spread in city areas is more complicated in terms of various types of terrain topology and architectures. With the fast development of urbanization, our cities are booming in both number and their sizes. As the combustible materials are accumulating to a critical volume, we are more likely to be opposed to the potential fire hazard [1]. The disaster, though occurs occasionally, threatens our lives and causes significant property losses. In 1906, following the earthquake (M7.8), fire spread in San Francisco destroyed 492 city blocks and killed more than 3,000 people [2]. In 1943 and 1945, huge fire disasters in Hamburg and Hiroshima were caused by battlefields [3-4]. More recently, in 1995, Kobe was reported 148 fires in the first 3 days after the earthquake, which caused 500 deaths, and damaged more than 6,900 buildings [5].

Since huge city fires are rare, computer models of fire spread in city areas can be very useful for helping to estimate, understand, reduce, and prepare for fire losses [6]. This paper introduces a new simulation model developed to improve the estimation of fire spread in cities.

A large amount of scholars around the world has investigated the problem of city fires seriously. So far, three major categories of the city fire models are conducted to simulate the process. They are empirical models, probability models and physical models [7]. Empirical models, which are largely developed by Japanese scientists, have generalized empirical formulas according to historical data. They are simple in mathematic structure and easy to calculate. But they are loosely tied to the physical principals of city fire, and weak in portability. Probability models, which match the indefinite nature of fire spread in cities, adopt mathematical equations to describe the stochastic process of city fires. Though they have strong mathematical logic to support the models, like empirical models, they are weak in fire physical principal connections. Moreover, due to the use of numerous statistical parameters, they have high demand for calculation resources [8]. Physical models, which adopt fire spread rules to demonstrate the process of city fires, are more related to the real process the fire happens and spreads [9]. However, they also have weaknesses in computational efficiency. Especially when we want to simulate in large open areas, the whole process could be too complicated to calculate [10].

Recently, cellular automation model is broadly used in simulating fire spread process. Due to its capability of describing a dynamic system in discrete time and space, the model can be adaptive to many applications. When simulating large-scale fire spread, the scattered lattice gird could be viewed as the cells, which are the fundamental operating units of the model. Since all the cells are subjected to the same rules and updated their statuses simultaneously according to the boundary conditions [11], the whole calculation process shall be quite simple. Each individual cell computes its own status according to the rules it shall obey without considering the other cells. However, despite the model's simplicity and effectiveness, the traditional cellular automation model simulating the fire spread process neglects the hybrid properties of the cities, including both forests areas and building areas in one city, that fails to make a trustable outcome of the simulation [12].

Note that city fires do not usually come along, it always occurs with other disasters. For example, after a significant earthquake, many fires may ignite simultaneously throughout city areas as a result of electric arcing due to short circuits, disrupted gas flames on appliances, and overturned candles [13]. So far, fire spread models do not usually interact with other disaster models and few standardizations for uniformed communication strategies in disaster model management is established. This could be a problem, since in many cases, especially in emergency management scenarios, we should involve the fire spread models into other related disaster models and interact with them [14]. Only by this way can we make the informed decision in disaster rescue.

In this paper, a GIS based dynamic modeling of fire spread with heterogeneous cellular automation model is proposed. Different types of cells and their properties applied in various city elements are described in the paper. Besides, we have also established a B-S standardized protocol, which is based on Web Processing Service (WPS), to integrate the fire spread model into a set of disaster models and help them interact with each other.

This paper is organized as follows. Section 2 depicts the methods of building models, including cellular automation model of fire spread in forests, building cell status, cellular automation model of fire spread within a concrete building and among different buildings. Section 3 articulates the method of using heterogeneous cellular automation models to simulate the city fires in hybrid scenarios. Section 4 presents the standard protocols for disaster models management. Section 5 concludes the paper.

2 MODEL DESCRIPTIONS

2.1 Cellular Automation Model of Fire Spread in Forests

When using cellular automaton model to simulate fire spread in forests, we usually divide the simulation areas into grids with length *a*. The size of *a* should be chosen appropriately. If the value of *a* is too big, the effect of the simulation will be bad. On the contrary, if it is too small, the calculation could be too hard to implement. As shown in Fig. 1, Moore neighbors is presented to simulate the fire spread process in forests [2].

i-1, j-1	*i-1, j*	*i-1, j+1*
i, j-1	*i, j*	*i, j+1*
i+1, j-1	*i+1, j*	*i+1, j+1*

Fig. 1: Moore neighbors

The status of cell (*i, j*) at *t+1* is determined by its status at *t* and the velocity of fire spread to it from its Moore neighbors. Eq. (1) shows the parameters contributing the fire spread velocity in forests [7].

$$\mathrm{R} = R_o K_s K_\varphi K_\omega \tag{1}$$

Where K_s stands for the adjusting parameters of the forest type. Table 1. shows the value of K_s in terms of the forest type.

Table 1: Forest Types with Different K_s Values

Forest Types	Rivers, concrete buildings, barren lands	Farm lands	Broad-leaved forest	Mingled forest	Bush	Grass lands	Coniferous forest
K_s	0	1.0	1.3	0.5	1.0	1.5	1.8

K_φ represents the slope of the terrain between the two neighboring cells. Eq. (2) shows the K_φ value between the two neighboring cells.

$$K_\varphi = \mathrm{e}^{3.533(-1)^G \tan\varphi^{1.2}} = \mathrm{e}^{3.533(-1)^G \left|\frac{h_{k,l}-h_{i,j}}{a}\right|^{1.2}} \quad (2)$$

Where $\mathrm{h}_{k,l}$ stands for the height of the cell *(k, l)*. And $\mathrm{h}_{i,j}$ stands for the height of the central cell. From the equations, we can see that when $\frac{h_{k,l}-h_{i,j}}{a} > 0$, fire spread upwards could be intensified, on the contrary, if $\frac{h_{k,l}-h_{i,j}}{a} < 0$, the fire velocity could be slowed down.

K_ω is the adjusting parameter for wind, where $K_\omega = \mathrm{e}^{0.1783V\cos\theta}$, the θ stands for the rotation angel from downwind direction to the current wind direction clockwise.

2.2 Building Cell Status

In order to build our heterogeneous cellular automation model applied to hybrid city fires, it is important to review some foundations of using cellular automation models to simulate fire spread process. In cellular automation models, the base map is divided into small grips, which are also the individual working units calculating whether the fire has spread to its current position. In classical cellular automation models, the status of the cells could be in five phases, namely dormant, growth, fully developed, decay and extinguishment. As shown in Fig. 2, dormant phase indicates that no fire or ignition occurs in the current cell. And once ignition occurs in the current cell, fire might grow up to a fully sustained fire before flashover, during which is at the status of growth phase. When the cell reaches the status of fully developed after flashover, it has the capability to release heat and ignite neighbouring cells. When the burning fuels gradually wear out, the cell's status changes from decay to extinguishment.

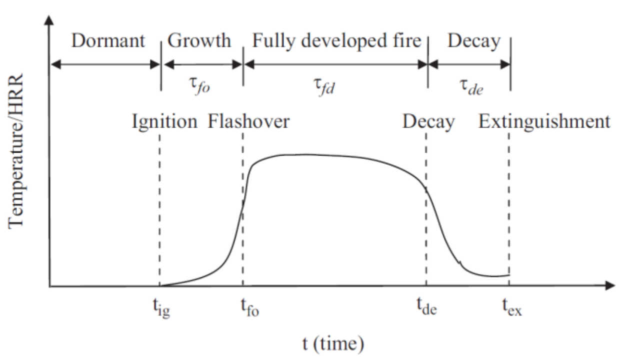

Fig. 2: The phases of enclosure fire development [3]

2.3 Cellular Automation Model of Fire Spread within a Concrete Building

Modeling fire from rooms to rooms within a building is the foundation of our work. And the physical principals of modeling the fire from one building to another due to radiation is the same as modeling fire spread within the building. Neighbors in fully developed status may ignite adjacent rooms through doorways and 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 [15], 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) decay (before extinguishment) and extinguishment, to form the basic elements of the model.

2.3.1 *Fire Spread within a Building through Horizontal Directions.*

According to the hypnosis above, each compartment (room) is represented as a cell in Cellular Automation Model. When calculating the fire spread in the same floor, whether a room is ignited is depending on two factors, the neighboring burning room is at the status of fully developed and the barriers between the burning room and the non-burning room fails. Only when the current room is at the status of fully developed and the barriers (mainly closed doors and windows) 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 Eq. (3) [16]:

$$t = \sqrt{\frac{750A_0\sqrt{H_0}}{\alpha}} \quad (3)$$

Where t is the time 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 2.

Table 2: 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 at the same floor is the barrier failure. We assume that the barrier failure conforms normal distribution [17]. Thus the density function of barrier failure is described by Eq. (4) [17]:

$$P_{bf}(t) = \frac{1}{\sigma_{bf}\sqrt{2\pi}} \exp(-[(t-t_0)-\mu_{bf}]^2 / 2\sigma_{bf}^2) \tag{4}$$

Then the probability of the barrier failure is represented by Eq. (5) [17]:

$$P_{bf}(t) = \int_{t_{f0}}^{t} \frac{1}{\sigma_{bf}\sqrt{2\pi}} \exp(-[(t-t_{f0})-\mu_{bf}]^2 / 2\sigma_{bf}^2) dt (0 \le t - t_{f0} \le \tau_{fd}) \tag{5}$$

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.

2.3.2 *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. [19], in order to transmit the fire flame, wind velocity must reach a critical value, which is described in Eq. (6):

$$V > \sqrt{2(1-\frac{T_0}{T_g})gH / (C_{p,W} - C_{p,L})} \tag{6}$$

In Eq. (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.

2.4 The Modeling of Fire Spread among Buildings

Radiation ejected out from burning rooms by gas and flames fluxes 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 [20]. In our model, we have carefully considered the configuration factors. Besides radiation, branding is also another significant way to transmit fire. And we will discuss the process in this section.

2.4.1 *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 [21]. And Eq. (7) presents the method to calculate the configuration factor from surface A to surface B [21]:

$$F_{1\to 2} = \frac{1}{A_1}\int_{A_1}\int_{A_2} \frac{\cos\theta_1 \cos\theta_2}{\pi s^2} dA_2 dA_1 \tag{7}$$

Where θ_1 and θ_2 are the angles of the ray and the perpendicular line between the two differential areas of the surface [21]; and *s* is the length of the ray.

2.4.2 *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 3 [22].

Table 3: 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 that the duration of each time step is 5 minutes, then according to the data in the Table 3, 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 Eq. (8) and Eq. (9) [20]

$$I_z = \phi_z \varepsilon_z \sigma (T_z^4 - T_a^4) \tag{8}$$

$$I_f = \phi_f \varepsilon_f \sigma (T_f^4 - T_a^4) \tag{9}$$

where T_f, T_z and T_a are the temperatures of the burning 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.

2.4.3 *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 [23]. It can ignite cells far away by carrying the burning sphere-like grains from the current fire spreading areas via wind. 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.

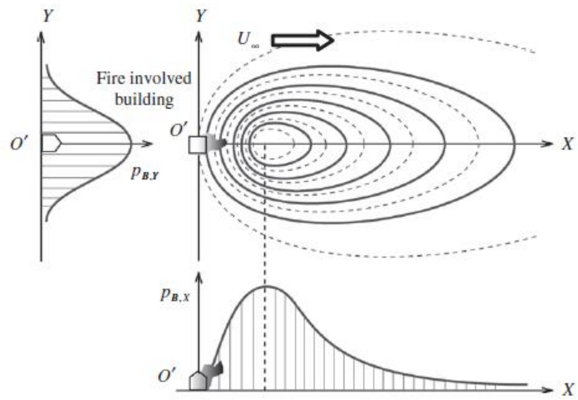

Fig. 3: Himoto and Tanaka's probabilistic brand transport model [23]

Fig. 3 describes the stochastic process of the firebrand scattering emitted from a burning building [23]. 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 Eq. (10) and Eq. (11).

$$P_X = \frac{1}{\sqrt{2\pi}\sigma_X X}\exp\{-\frac{(\ln X - \mu_X)^2}{2\sigma_X^2}\} \tag{10}$$

$$P_Y = \frac{1}{\sqrt{2\pi}\sigma_Y}\exp\{-\frac{Y^2}{2\sigma_Y^2}\} \tag{11}$$

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.

3 METHOD OF HETEROGENEOUS CELLULAR AUTOMATION MODELS TO SIMULATE THE CITY FIRE IN HYBRID SCENARIOS

3.1 Partition of the Heterogeneous Cells

So far, we have discussed the cellular automation models applied to different scenarios in city fire context. To integrate them as a whole, and run the simulation of the heterogeneous cellular automation model, it is quite important to segment the base map to distinguish the different regimes and value them in different cells' properties. In our city fire spread model, the base map can be segmented into two parts, one is the forest regions (trees, parks, or forests near the city), and the other is buildings areas. Since the two different areas have different burning properties, we should value them in different cell types. As we have discussed above, in forest areas, the land could be divided into grids with the same size, and the building areas, however, should be viewed as a set of cells collection, where each compartment is viewed as a cell. Fig. 4 shows a typical segmentation of the urban area.

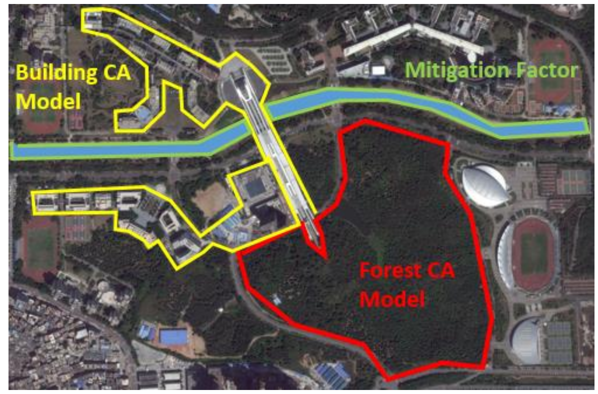

Fig. 4: Base map segmentation

In Fig. 4, the areas circled by red is the forest area, where all the cells should conform to the forest cellular automation model. And areas circled by yellow is the building area, whose cells should be applied to the building cellular automation model. Note that there is a river circled by green that is viewed as the mitigation area, fire shall not transmit through the area. And only the branding process can help to transfer fire to another side.

There still remains a question that how can the fire transmit from forest areas to building areas or from building areas to forest areas, since it is obvious that there is a boundary between forest areas and building areas. In classical physical fire spread models, fire spreads because the radiation transmits from the current burning objects to the subject that is going to be ignited. Considering the cases that the fire transferring from forest areas to building areas, since forests fire emits a large amount of heat, the building next to the boundary is very likely to be ignited in the next time step when the fire spreads to the boundary. And in the case of fire spreads from building areas to forests areas, forests are unlikely to be ignited since the heat released from the compartment is comparatively small.

Another possible way of transferring fire is branding. Since branding is a stochastic process, it can cause fire whether from forest areas to building areas or vice versa.

4 STANDARD PROTOCOLS FOR DISASTER MODELS MANAGEMENT

City fires do not usually occur along. They always come with other disasters. For example, a major earthquake could lead to ignition spots scattered around the city, which may cause huge city fires. In complex disaster model management, it is always required to make use of several disaster models together to tackle complicated problems. Different disaster models do not usually integrate in a fixed server. They are, actually, installed in a distributed way. So there is need for building a common standard protocol to organize all the disaster models and help them interact with each other.

Since all the models are deployed in a distributed manner, building a web based protocol structure will help to solve the problems. By developing a B-S management structure of the disaster models, we are able to integrate all the disaster models and make them work together under standardized management.

As shown in Fig. 5, the users from the web-side could access the specialized disaster models through URL. Then the server-side will accept the Web-side user's requests. After interacting with the database and calculating the models with the input parameters, the result should be sent back and visualize to the user in the web-side.

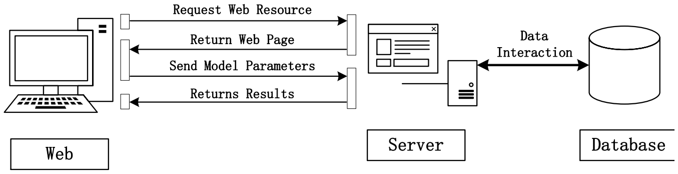

Fig. 5: B−S **management structure**

In the simulation process, the user visits the Web interface of the fire simulation system, creates the fire points and sets the fire model parameters. Then the web-end sends the parameters to the server side in the standard XML data format. The application service program on the server side calculates the fire model according to the parameters. Finally, the simulation data is sent back to the web-end in standard JSON format, and the web browser resolves and displays the simulation data.

5 SIMULATIONS AND DISCUSSIONS

5.1 Simulation Conditions

In order to verify the model, several simulations were conducted in the area of the University Town of Shenzhen. As shown in Fig. 6, by setting the parameters and ignition point, our simulation program will calculate the fire spread range and demonstrate it on the platform in every time step. In the experiment, our program is supposed to calculate the fire spread range every 5 minutes. Each circle stands for the calculation result of each time step. As a consequence, you can see the fire spread range at 5 minutes, 10 minutes and 15 minutes respectively under the conditions of environmental and cellular settings.

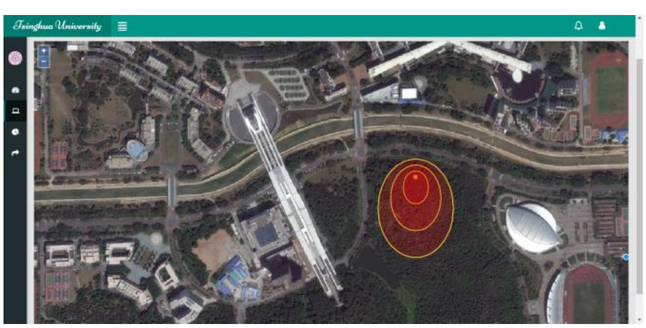

Fig. 6: Fire simulation platform

The fire was started at the forest area of the University Town of Shenzhen. Reference wind velocity is varied from 3, 12, to 24 m/s. And the rest of the parameter settings related to the fire spread are shown in Table 4.

Table 4: Parameter Settings Related to the Fire Spread

Parameters	Values
Wind Direction	South
Wind Velocity	3, 12, 24 m/s
Temperature	30℃
Humility	80%
Length of the Cell	1 meter
Time Slot of Each Calculation	5 minutes
Simulation Time	15 minutes
The Numbers of the Status of the cells	5

5.1 Results and Discussions

In a sequence of time, examples of simulated fire spread are shown in Fig. 7. In this simulation, the wind blows south. The yellow point indicates the ignition point. The red circle stands for the fire spread range within each time step. Column (A) illustrates the simulation results at V = 3 m/s, column (B) illustrates the simulation results at V = 12 m/s, and column (C) illustrates the simulation results at V = 24 m/s.

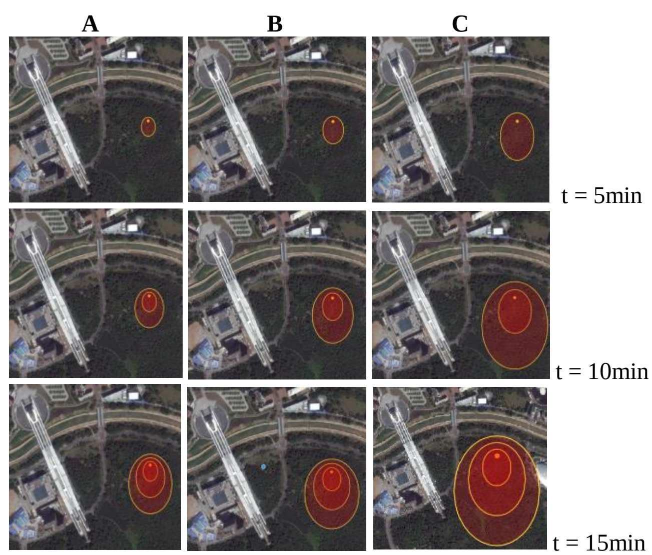

Fig. 7: Results of fire spread simulation. (A) V = 3 m/s, (B) V = 12 m/s, (C) V = 24 m/s

From the images above, it is quite obvious that the fire spread rates increase with the increment of wind velocity. At present, we have only considered the conditions when fire spreads in forest areas. In the future, simulations of fire spread in a more hybrid scenarios will be implemented, and the fire mitigation factors will also be taken into account.

6 CONCLUSIONS AND OUTLOOK

In our work, we have established the fire spread models applied to hybrid urban scenarios that uses the heterogeneous cellular automation models to simulate different types of city areas (forests areas and building areas). And the B-S based standard protocols for disaster models management is presented to organize the model in a better way. And the standard protocols will also provide us a disaster model management prototype, which enables different disaster models to interact with each other and make synergy efforts. At last, a comparison of experimental results with different wind velocity is carried out to illustrate the model.

In the future, the simulation part will be further implemented. Different cellular types representing different structures in urban will be considered. As a more mature model, buildings with various construction materials and structure have different cellular types with different properties. And the interface between the forest areas and building areas should be well defined to model the transition phase of the fire spread from forest to urban and vice versa. Besides, comparisons between our methods of modeling the fire spread and other classical methods will be conducted as our future work. Furthermore, in the real fire spread case, mitigation factors usually plays a very important role to restrict the fire spread process. As a consequence, mitigation factors should be highly investigated when modeling the fire spread process. In the future, mitigation zone, fire rescue power and natural environmental factors will be considered to make our model more practical and useful.

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