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SIMULATION OF SPREADS OF FIRE ON CITY SITE BY STOCHASTIC CELLULAR AUTOMATA

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SUMMARY

Earthquakes often cause serious fires. At 1995 Hyogo-ken Nanbu earthquake, a lot of houses were burnt down and many lives were lost especially at Nagata Ward. In order to build a city strong against disasters, it is indispensable to take fire prevention measures. For that purpose, we need to know correctly how a fire spreads on a city area. Though, many complicated factors are related and make the numerical prediction difficult. In this study, the spread of a fire on a town block is modeled using cellular automata (CA). Since the degree of damage is various even if buildings suffer from the same earthquake, this model employs stochastic method. The proposed stochastic CA model can include such uncertain and complex characteristics of the spread of a fire easily. Using this model, at first, simple simulations are carried out and the basic behavior of the model is checked. Next, the spread of a fire in Wakamatsu-cho, Nagata Ward at 1995 Hyogo-ken Nanbu earthquake is simulated and the result is compared with the actual data. At the end, the protection against the spread of a fire in this area is discussed in this model's context.

INTRODUCTION

Earthquakes often cause serious fires. At 1995 Hyogo-ken Nanbu earthquake, a lot of houses were burnt down and many lives were lost especially at Nagata. Asian cities have a lot of old wooden house yet. If a great earthquake occurs in these cities, fire damage may become enormous. In order to build a city strong against disasters, it is indispensable to take fire prevention measures. For that purpose, we need to know correctly how a fire spreads on a town block.

Although 1995 Hyogo-ken Nanbu earthquake was an unfortunate occurrence, it left many precious data about disaster measures of urban areas. New simulation models of the spread of fires are currently developed and compared with these actual data. Many of them employ a model called Hamada's method as a basic model. Hamada's method is a formula which is devised from data such as past fire records and fire experiments of buildings and calculates the time until a building is ignited. Parameters are width of one side of a building, distance until a neighborhood building, and the effect of wind and so on. Once they are inputted, the time until a building is ignited can be calculated. However, calculation is relatively complicated and it takes not a little costs and times to build the simulation model which suits to an actual city.

First of all, many complicated factors are related to the spread of a fire and make the numerical prediction difficult. Therefore, the model which does not much stick to its details but considers uncertain characteristics of the phenomena should be needed. The concept of this model is one of the views of "complex systems" studied widely in recent years [Worldlop, 1992]. The model called cellular automata (CA) is used frequently for modeling propagation-diffusion processes like the spread of a fire. CA was originated by von Neumann at the beginning of 1950s when he was studying the self-reproducing machine [Neuman, 1966]. CA is defined by discrete time, space, and states. A state of a cell changes according to the states of self and the neighboring cells.

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The model employing CA is very simple and the time of calculation is very quick by its simple structure. However, the phenomenon reproduced by the model is very similar to the actual one. From such features, CA is applied to reproduce various phenomena, such as traffic jams, forest fires [Resnick, 1995], and formation of urban land-use patterns [Takizawa et al., 1997], and so on.
In this study, the spread of a fire on a city area by an earthquake is modeled using CA. Since the degree of damage is various even if buildings suffer from the same earthquake, this model employs stochastic method. The proposed stochastic CA model can include such uncertain and complex characteristics of the spread of a fire easily. Using this model, at first, simple simulations are carried out and the basic behavior of the model is checked. At the next step, the spread of a fire in Wakamatsu-cho, Nagata Ward at 1995 Hyogo-ken Nanbu earthquake is simulated and the result is compared with the actual data. At the end, the protection against the spread of a fire in the area is discussed in this model's context.

MODEL

Space and elements

A city area is occupied with various elements such as buildings, roads, parks and other uses. These elements differ in size, form, structure, and function. However, a city area is modeled very simply in this study. It is divided into a two-dimensional cellular space. The size of a cell is about 5 meters per side. Heights of cells are supposed to be same. Each cell shows one of the following four city elements and any other elements are not considered. Only wooden cells can burn, and other cells work to prevent fire from spreading.

1) Wooden cell: a wooden house
2) Fire proof cell: a fireproof building
3) Road cell: a part of roads
4) Vacant cell: a vacant or other used space.

Burning process of a wooden house

The general burning process of a wooden house is as follows. A fire is restricted to burn around the ignited point for a while after outbreak of the fire, and the range of burning expands gradually. This stage is called "initial fire". Then, the fire becomes most violent through the explosive burning state of "flashover." This stage is called "fire peak". In order to simplify, these two stages of burning are packed to one state in this model. Finally, three states about burning of a wooden cell are defined as shown in Figure 1. Normal state represents a usual wooden house and has the potential of ignition from burning state cells in its neighborhood. If a normal state cell is ignited, the state turns to burning state. Burning state represents a fired wooden house and has ability to spread its fire to the neighboring cells. Burning state continues for *Buringtime* and then the state turns to burnt state and the wooden cell becomes ash.

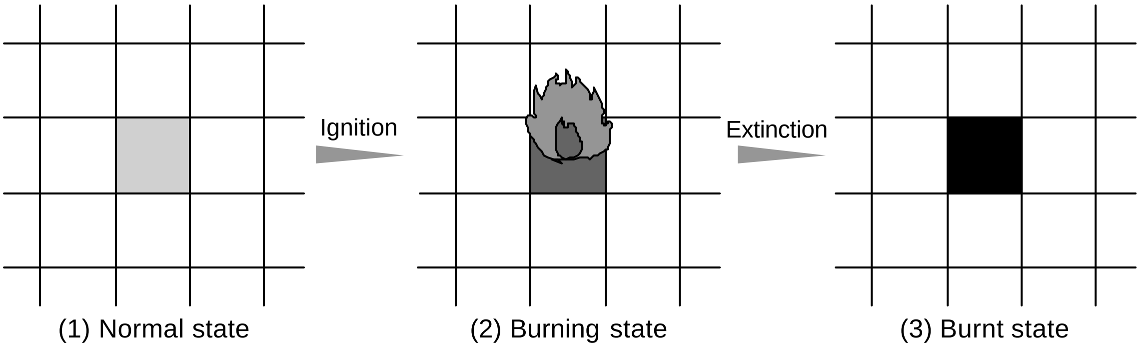


Figure 1: Three states about burning of a wooden cell

The flowchart of the judgement whether a normal state cell can be ignited or not is shown in Figure 2. A burning state cell searches its neighborhood. If the cell satisfying the condition is found, the cell is checked the judgement of ignition. The neighborhood is defined as its immediate four cells and ones which are at one more distance. Since the effect of wind is not considered, fires can spread to all directions equally.

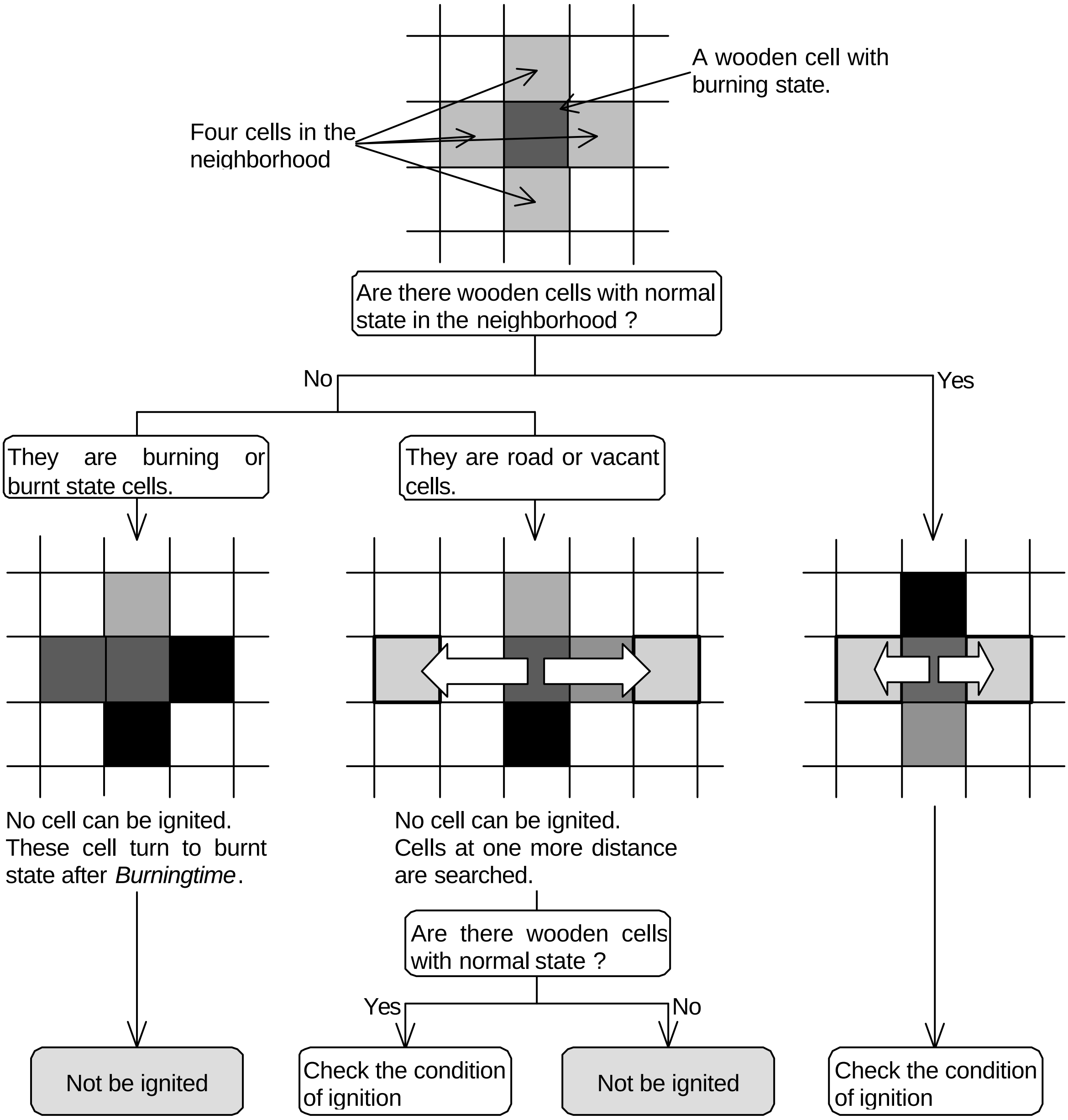


Figure 2: Flowchart of the judgement of ignition

The condition of ignition is defined as equation (1). This condition is calculated at every searched cell with normal state. If this condition is satisfied, the state of the cell turns to burning state.

$$Propability >= \text{Random} \times DisFactor(d) \tag{1}$$

here
Probability: The degree of ignition of a wooden cell (0.0~1.0)
Random: A random number (0.0~1.0)
DisFactor(*d*): The gradual diminution rate by the distance "*d*" from burning cell (0.0~1.0). "*d*" is 1 (immediate neighborhood) or 2 (one more distance). *DisFactor*(1) is fixed to 1.0. *DisFactor*(2) is a parameter.

The flow chart of the simulation is show in Figure 3. First some normal cells are ignited and they become burning state. Then burning state cells are listed and normal state cells in their neighborhood are searched. If there are cells satisfying it, they are judged whether ignited or not, and the cell which can pass the judgement burns. The time of burning is incremented and if it reaches at *Burningtime*, the cell turns to burnt state. If there are burning state cells, they are listed and operations mentioned above are repeated. This cycle is defined as 1 *Timestep*. If there is no burning state cell, the simulation terminates.

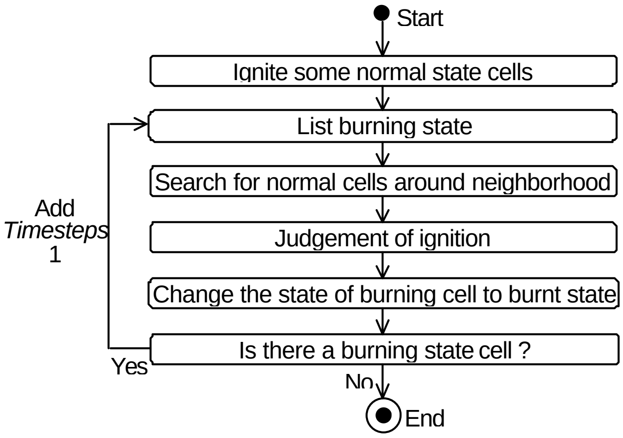


Figure 3: The flow chart of the simulation

SIMULATION

Simple simulation

Space and parameters

At first, simple simulations are carried out to examine the basic behavior of this model. The size of the space is 50x50 and all cells are wooden ones. A center cell is ignited and maximum ranges of spread of the fire are exmained. Values of parameters are as follows:

Case 1: *Probability* is changed from 0.0 to 0.4, *Burningtime* is fixed at 4.
Case 2: *Probability* is fixed at 0.1, *Burningtime* is changed from 1 to 15.

Result

Simulations with 10 different initial values of random numbers are carried out. Figures 4 and 5 shows results by each random numbers and averages of all results. Figure 4 shows the result of Case 1. Number of burnt cells increases steeply from the point at which *Probability* is over 0.15. Figure 5 shows the result of Case 2. Similar to Case 1, number of burnt cells increases steeply from the point at which *Burningtime* is over 5. Dispersions of results by different random numbers are relatively large around steep slopes. If the condition of a city area is near the steep slope, the degree of spread is very unpredictable. In both cases, extents of the spread of a fire expand all at once with the increase of the degree of ignition. Such phenomenon is called "self-organized criticality" [Bak et al., 1988]. This means that the danger of the spread of a fire is not gradually but catastrophically increases as the resistance to a fire of each building decreases. Now let's suppose that some efforts can reduce *Probability* by 0.1 in Figure 4. If the condition of a area is near the steep lope (*Probability*=0.2), the area can be changed to be safe (*Probability*=0.1) by the effort. However, if the condition is far from the slope (*Probability*=0.4), the extent of the spread of a fire can not be reduced (*Probability=0.3*).

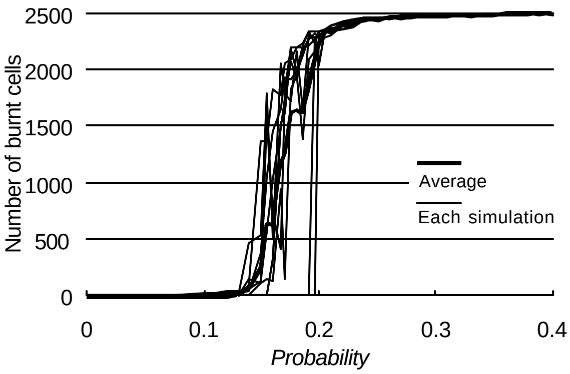


Figure 4: Result of Case 1

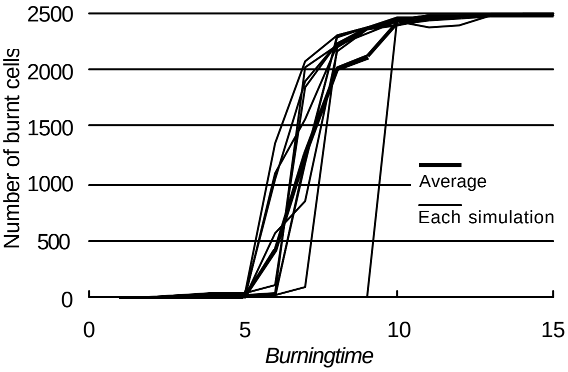


Figure 5: Result of Case 2

From the viewpoint of engineering and urban planning , it is interesting to examine the degree of *Probability* and *Burningtime* of actual city area. In the next section, the authors apply this model to the actual spread of a fire and examine them.

Application to the spread of a fire in Nagata Ward at 1995 Hyogo-ken Nanbu earthquake

The applied area and parameters

Next, this model is applied to the actual spread of a fire in Wakamatsu-cho, Nagata Ward at 1995 Hyogo-ken Nanbu earthquake (Figure 6). Nagata Ward was a downtown of Kobe and consisted of many old wooden houses and narrow roads remained. Wakamatsu-cho was residential area and some shopping districts went through along streets. The fire broke out at about 5:47 from the southeast part of the area and 683 houses and buildings were burnt down until about 20:45. Wooden houses collapsed over narrow roads (4~6m) and fires spreads through these collapsed houses. Fires also spread though burning cars [Kobe city fire bureau, 1996a]. Wide roads (over 8m) and an elevated railroad stopped fires.

Though many factors mentioned above make difficult to simulate the spread of a fire precisely, this area is selected since the block pattern is simple and easy to be modeled by cellular space. Figure 7 shows the area modeled by a cellular space. Elements in the actual area are changed to one of the four uses. In the case that a building is larger than a cell, the building is represented by suitable number of cells.

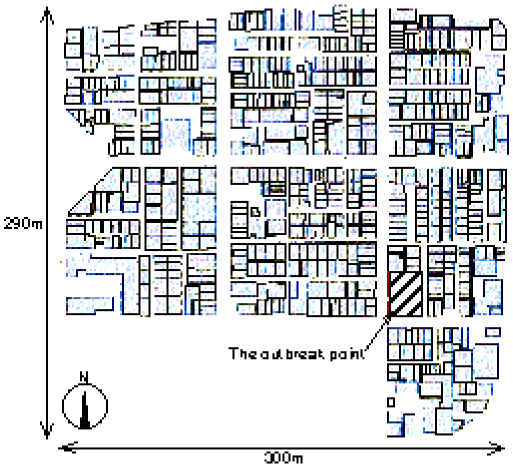


Figure 6: Wakamatsu-cho area [Kobe city fire bureau, 1996b]

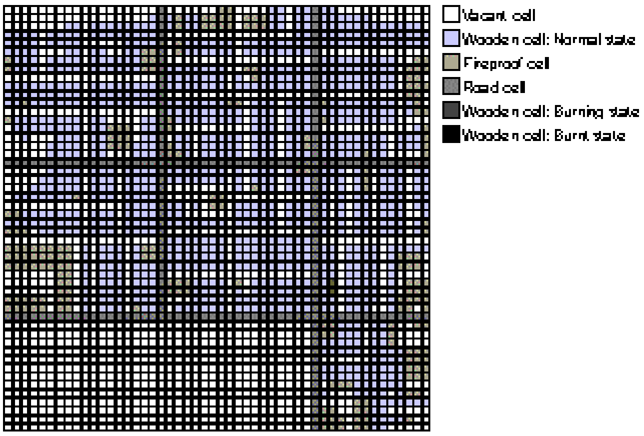


Figure 7: A modeled cellular space

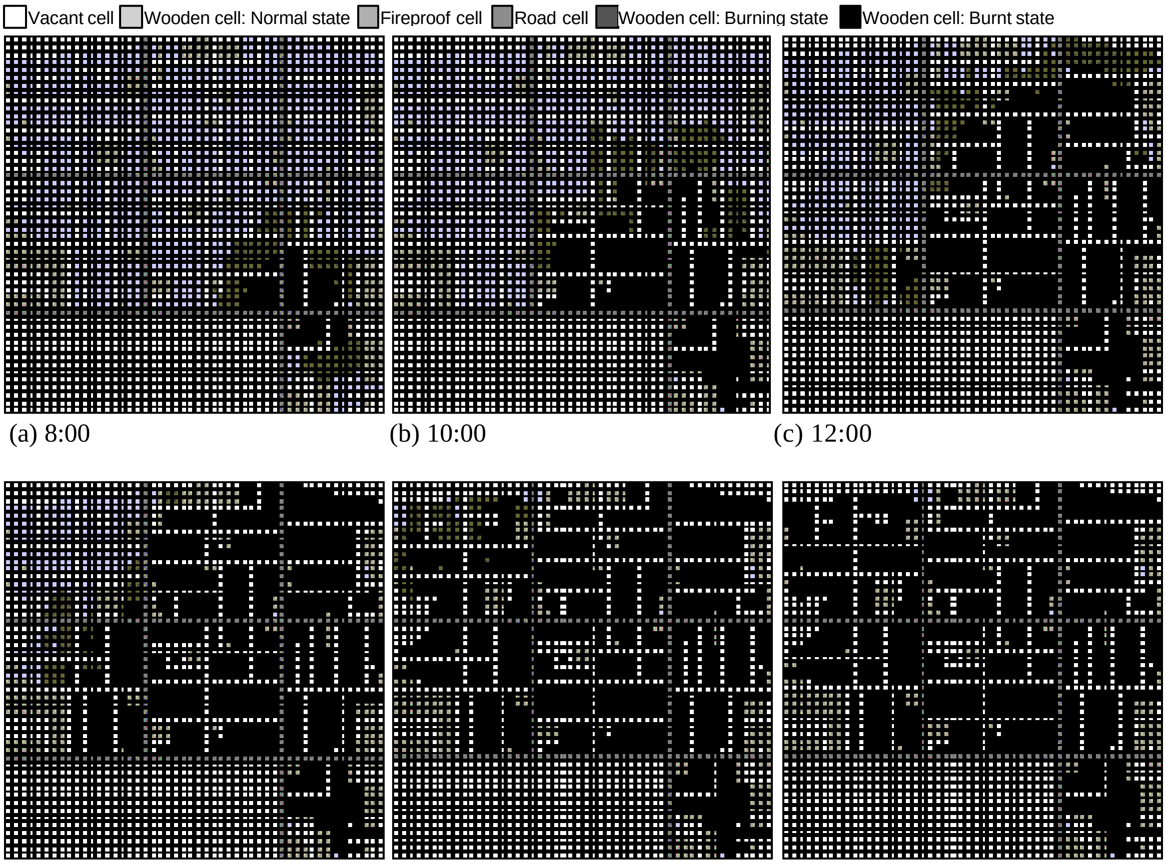
Parameters used in this simulation are shown in Table 1. At first, *Burningtime* is determined about 50 minutes. Then several preliminary simulations were carried out and the set of parameters which generates the most similar result is employed.

Table 1: Parameters

Parameter	Value
Timesteps	2756 (One hour is 225 *Timesteps*, 5:47~18:00)
Probability	0.01
Burningtime	190 (about 50 minutes)
DisFactor(2)	0.3

Results

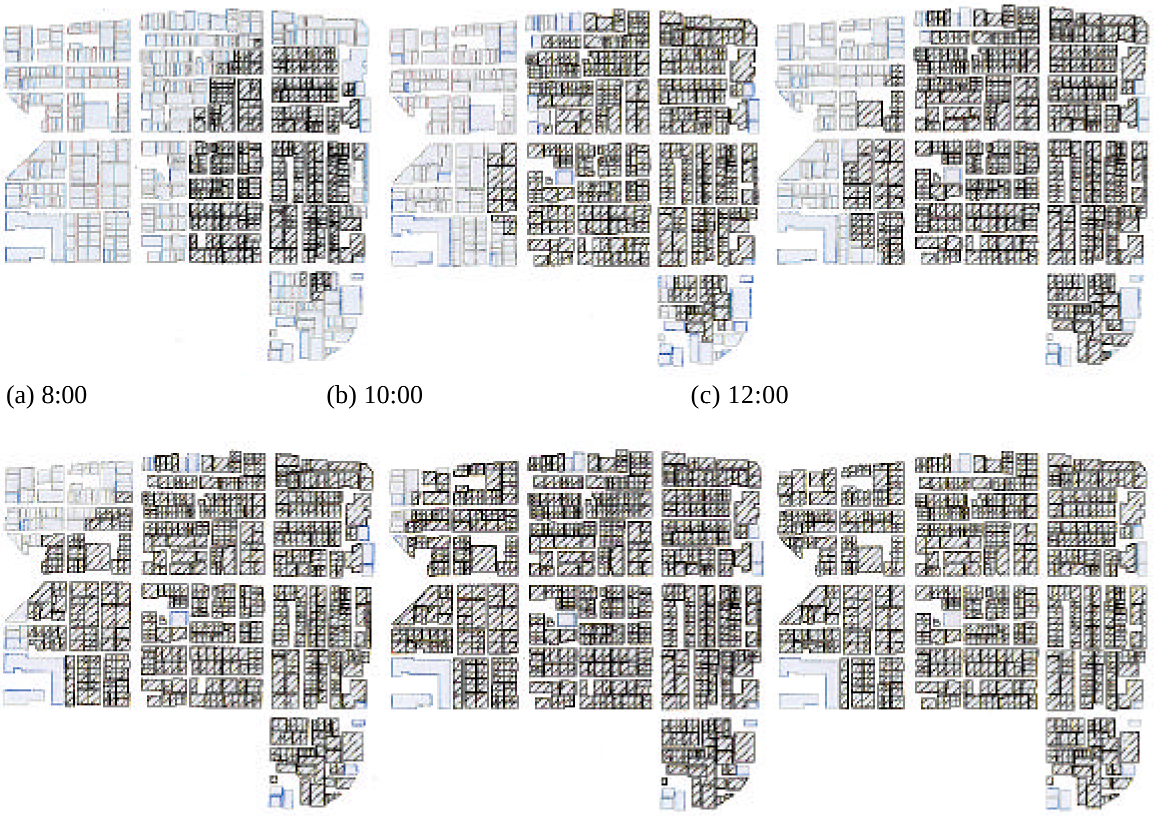
Figure 8 shows the result of the simulation. Figure 9 shows actual patterns of the spread of the fire in Wakamatsu-cho. Comparing both results from 8:00 to 12:00, the extent of burning and burnt cells in the north-south direction of the simulation is much less than the actual one. The reason is that the actual fire rapidly spread by the south wind and gas leaking for a while after the outbreak of the fire [Kobe city fire bureau, 1996a]. However, the area in the east-west direction of the simulation is close to the actual one. After 14:00, both patterns are similar. By employing CA, the process of the spread of a fire can be reproduced in high spatial resolution in spite of very simple rules



(a) 8:00 (b) 10:00 (c) 12:00

(d) 14:00 (e) 16:00 (f) 18:00

Figure 8: Result of the simulation



(a) 8:00 (b) 10:00 (c) 12:00

(d) 14:00 (e) 16:00 (f) 18:00

Figure 9: Actual spread of the fire in Wakamatsu-cho [Kobe city fire bureau, 1996b]

Figure 10 shows the accumulated numbers of burnt cells and houses. The result of the simulation is the process shown in Figure 8 and average of the simulations with 10 different random numbers. The difference between the result of Figure 8 and the average is small. The actual fire spread much faster than the simulation from 6:00 to 13:00. The reason is already mentioned above. After 13:00 the result of simulation is similar to the actual fire. The fire stopped until about 18:00. The time of the simulation takes about only 34 seconds (Pentium II Xeon 450MHz, 128MB, WindowsNT Workstation 4.0 Service Pack 4, Borland C++Builder 4.0 Professional).

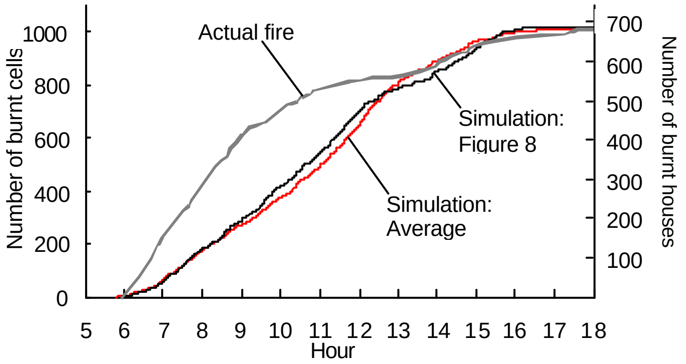


Figure 10: Accumulated numbers of burnt elements of the simulation and actual fire

DISCUSSION

This proposed model is very simple and one might say that it is too simplified. For example, the cell is not considered detailed stages of burning, the effect of wind, and other elements. In particular, the effect of wind is thought to greatly influence the spread of a fire. The result of the simulation in Wakamatsu-cho differs from the actual result for a while after the outbreak of the fire. However, these conditions are so complex and uncertain that the authors employ the stochastic method to make them a black box. Consequently, this model can generate not a little similar pattern to the actual one. The similarity lead to analyze this area's condition about the spread of a fire in the model's context. Parameters used in the simulation of Wakamatsu-cho are compared with the results of simple simulations.

Figure 11 shows this result. The horizontal axis shows values multiplied *Provability* by *Burningtime*, and here this value is called Total Probability. Total Probability is probability that a burning state cell ignites a immediate neighborhood cell while the cell is burning. The vertical axis shows the ratio of burnt elements (cells or houses). The results of simple simulations are averages. The ratio begins to increase at 0.5, and it almost 100% at a little over 1.0. A house needs to ignite at least one house if a fire spreads over an area completely. The value used in the simulation of Wakamatsu-cho is plotted at the point (1.9, 100%) far away from (1.0, 100%). This means that if a fire brakes out from any place in this area, this area will be completely burnt down. In other words, the protection ability of this area is very poor against the spread of a fire. In order to make Total Probability more real and reliable, more areas burnt down at 1995 Hyogo-ken Nanbu earthquake have to be examined. This is a future work.

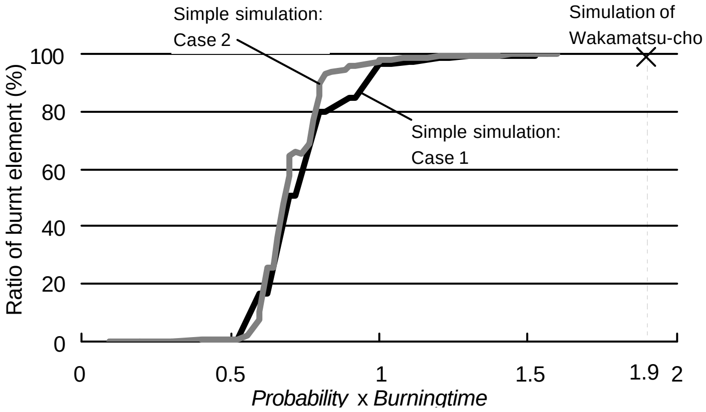


Figure 11: Mapping the results of simulations by "Total Probability"

CONCLUSION

In this paper, the authors propose a model of the spread of a fire by employing stochastic CA. At first, the model is explained. Then, using this model, simple simulations are carried out. It is observed that the range of burnt cells steeply spread as the probability of ignition increases. Furthermore, the actual spread of the fire in Wakamatsu-cho, Nagata Ward at 1995 Hyogo-ken Nanbu earthquake is simulated. Comparing both results, it can be said that this model can simulate the actual spread of the fire quite well in spite of its simplicity. The time of the simulation is also very quick. At the end, the protection against the spread of a fire in Wakamatsu-cho is discussed in this model's context, and it turns out to be very dangerous.

As future works, the effect of wind and more strict definition of burning states will be considered, and more areas will be simulated by this model.

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