DEVELOPMENT OF SIMULATION SYSTEM OF URBAN SPREADING FIRE IN AN EARTHQUAKE AND ITS APPLICATION TO DECISION OF EXTINGUISHING PRIORITY ORDER

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ABSTRACT :

The objective of this study is to develop the simulation system of the urban spreading fire in an earthquake in which the data for the simulation can be automatically made with the aid of digital residential map. Simultaneous occurrence of fires is one of the characteristics in an earthquake. Perfect fire fighting can not be expected under the special circumstances such as urban fire in an earthquake. Therefore, simulation of spreading fire plays an important role to make the most use of the capacity of fire fighting. It is required to build the analytical model of the target area for the simulation of urban spreading fire. The modeling often costs us tremendous labor and time. In this study, an automatic modeling system using digital residential map is proposed. Almost all the data, which are necessary for the simulation of urban spreading fire, cane be made automatically by just only assigning the target area in the map. The analysis of spreading fire is carried out by the algorithm of Petri-net which is one of graph theory. Based on this simulation system, the order of extinguishing priority can be determined by the comparison of the effect of extinguishment of each building on fire.

KEYWORDS: urban spreading fire, simulation, earthquake, automatic modeling, extinguishing priority

1. INTRODUCTION

Fires caused extensive damages to the cities around Kobe in Hyogo-ken Nanbu Earthquake (1995). We realized again the fear of fires in an earthquake. The fires in an earthquake are different from the regular fires. They generally occur simultaneously on a large scale, so that the activity of fire fighting is beyond its ability in almost all the cases. Since houses are densely built in the urban areas, there is higher risk to bring about a big fire. Perfect fire fighting can not be expected under the special circumstances such as urban fire in an earthquake. Then, simulation of spreading fire plays an important role to make the most use of the capacity of fire fighting. It is also practical and useful to evaluate the safety to a fire and to make a regional plan for disaster prevention.

Macro-simulation of spreading fire between grids (for example each grid is 5km×5km mesh) over the urban area had generally been performed based on such information as the building coverage ratio. The improvement of the accuracy in the formula of spreading fire and development of GIS (Geographic information system) enabled *micro-simulation* of spreading fire between houses. Some researches on the *micro-simulation* of spreading fire in urban areas have been done. For example, Yano, *et al*. (1996) applied their original formula of spreading velocity of fire to the simulation of the fire in Kobe in 1995 Hyogo-ken Nanbu Earthquake. Sekizawa, *et al*. (2000) utilized digital residential map for modeling the paths of spreading fire and they developed the system to perform the simulations with given wind velocity, wind direction and origin of fire. Tsujihara, *et al*. (2003, 2004) also proposed the system to simulate urban fire in an earthquake in which digital residential map was used. Later, Tsujihara, *et al*. (2005) modified the system by introducing the Perti-net (: e.g. Reising (1992), which is one of the graph algorithms and was defined in 1962 by Carl Adam Petri, so that it could be applied to the simulation of the simultaneous occurrences of fires. Tsujihara, *et al*. (2006) confirmed the validity of the system through the simulation in the burnt area in Hyogo-ken Nanbu Earthquake.

There are two major objectives in this study. The first is to develop the Tsujihara's simulation system of spreading fires so as to enable the easy creation of data of the analytical model in the urban area. Almost all the data, which are required in the simulation of spreading fires, are made and written in the corresponding files by just assigning the target area on the residential map in the computer display. The second is to apply this simulation system to the decision-making of extinguishing priority order.

2. ANALYTICAL MODEL AND OUTLINE OF METHOD OF SIMULATION OF SPREADING FIRES BY PETRI-NET

2.1 Modeling

A house is modeled with some places as shown in Figure 1. A couple of places are connected by input arc, transition and output arc as shown in Figure 2. Each place can hold tokens. The distribution of tokens represents the state of a system. An arc may have the weight which is shown by the number of arrows or accompanying integral number. The transition ignites when the number of tokens held in the input place is as same as the weight of the connecting input arc. Then, the tokens of the input place are consumed and the tokens, the number of which is specified by the weight of the output arc, are generated in the output place. The spreading time of fire, which can be calculated by the TFD (Tokyo Fire Department) formula, is allocated to the weight of each input arc. Figure 3 shows an example of the Petri-net modeling. The arcs connecting the places which belong to the different houses are also prepared with those weight calculated by the TFD formula. The outline of TFD formula of spreading velocity "Toshoshiki 2001" used in this study is mentioned in the followings.

The formula of the spreading velocity of fire is given to the wooden, wooden fire-preventive, quasi-fire-resistive and fire-resistive types of houses and buildings. Moreover the collapsed and partly collapsed houses can be considered. The spreading velocity of fire inside the wooden and wooden fire-preventive types is 52.1m/h and 42.8m/h, respectively. As to the quasi-fire-resistive and fire-resistive types, they are classified into 3 levels according to the usage of building and each spreading velocity is defined as the function of the size of building and the damage rate. The damage rate is related to the seismic intensity. The spreading velocity of fire between the houses or buildings is represented as the function of such parameters as seismic intensity and wind velocity. It varies with the combinations of types of constructions.

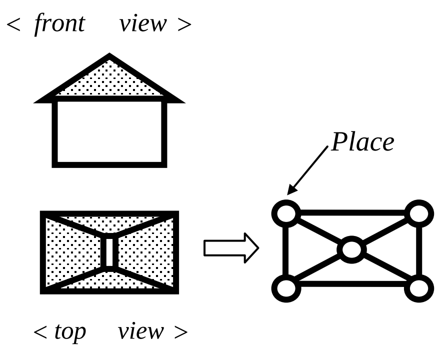


Figure 1 Modeling of a house

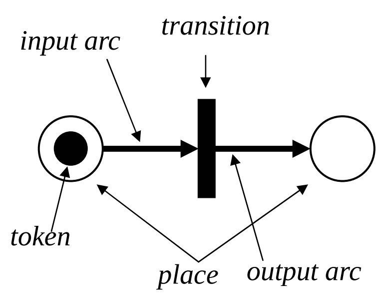


Figure 2 Petri-net

2.2 Rules of Analysis by Petri-net

The rules developed for the analysis of spreading fire is based on the colored Petri-net in which every token has the type. The three types of tokens in Table 1 are used. Let us explain the rule and the flow with Figure 4. The Petri-net model in Figure 4 has 3 places ($P=\{p_1,p_2,p_3\}$) and 2 transitions ($T=\{t_1,t_2\}$) and arcs. The initial marking is shown in Figure 4 (a), which indicates that p_1 is the place of initially burning. The token *A* is placed in p_1. The place which holds token *A* generates token *B* in one (analytical) step. One step corresponds to, for

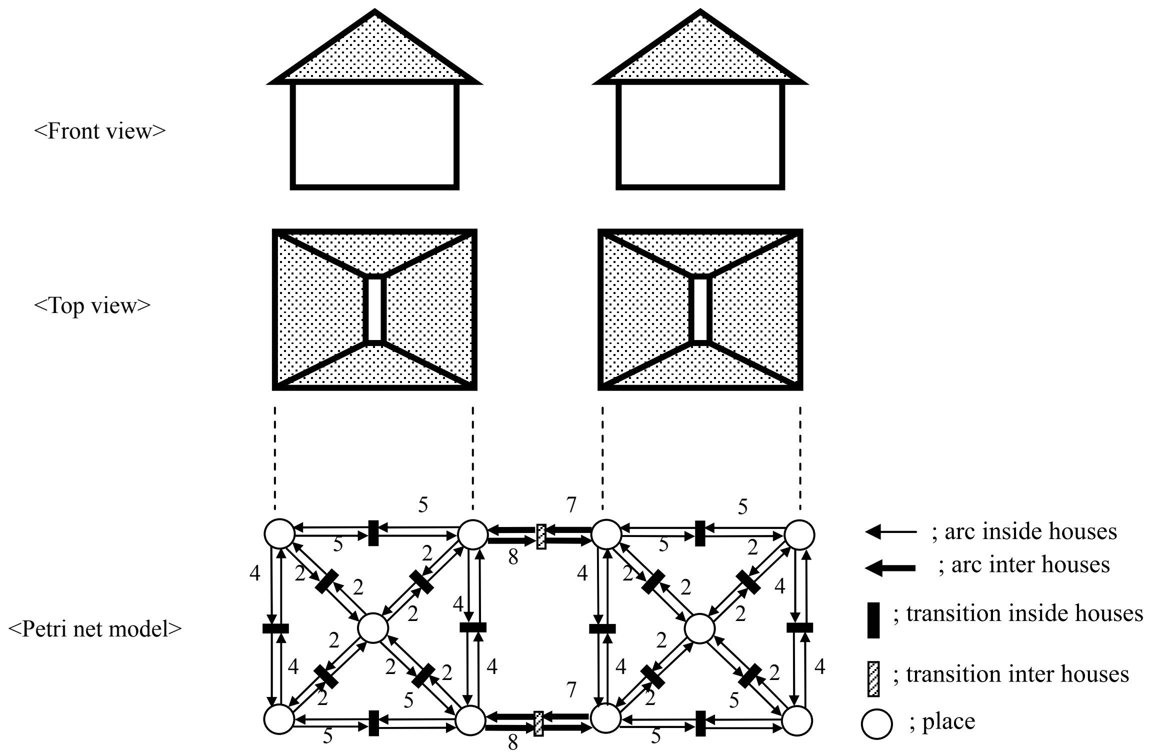


Figure 3 Petri-net modeling for simulation of spreading fire

example, one minute. Place p_1 holds two tokens *B* after two steps as shown in Figure 4 (b). Then since the number of tokens *B* in p_1 equals to the weights of the arc to the transition t_2, the copy of token *A* moves to p_3, but not consuming the tokens in p_1 as shown in Figure 4 (c). Place p_3 is to start burning after two steps; i.e., two minutes. After three steps, another token *B* is generated in p_1, and the number of token *B* in it equals to the weights of the arc to the transition t_1. Then the copy of token *A* moves to p_3 as shown in Figure 4 (d). A token *B* is generated also in p_3. In the step 3, all the output places from p_1 hold the token *A*, and p_1 generates a

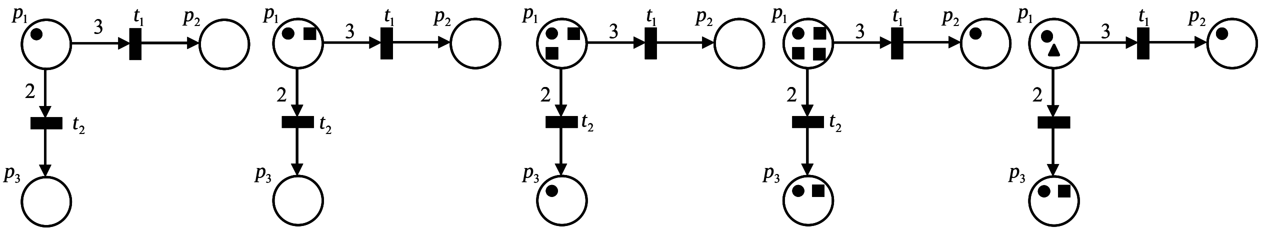
Table 1 Types of tokens and their roles

Shape	Name	Role
●	*A*	indicate burning
■	*B*	counter for *firing*
▲	*C*	indicate finishing *firing* from connected transitions

token *C* consuming the tokens *B* in it as shown in Figure 4 (e). Once a place holds a token *C*, it does not generate any more tokens, nor does it accept them. By memorizing the analytical step number when each place get the first token *A*, time to catch fire for each place is figured out. And by memorizing the number of place which sends a copy of token *A*, the paths of spreading fire can be identified.

3. AUTOMATIC DATA CREATION OF ANALYTICAL MODEL

In the system proposed by Tsujihara *et al.* (2005), each house in the computer display should be mouse-clicked to create the data of its analytical model. In the case that the number of vertices of the plane shape of a house is over 4, the approximate quadrilateral shape must be used. Moreover, any two places which belong to the different houses should be mouse-clicked successively to create the data of the arcs and transition connecting the places. These operations



(a) step0 (b) step1 (c) step2 (d) step3 (e) step3'

Figure 4 Marking in colored Petri-net

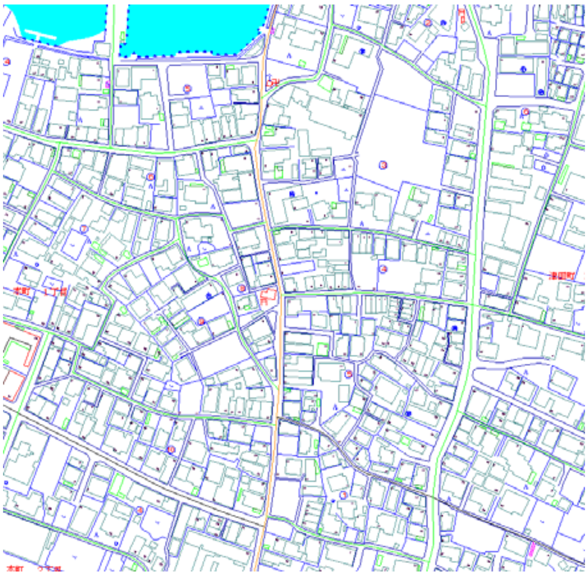


Figure 5 Residential map

Figure 7 Model of houses

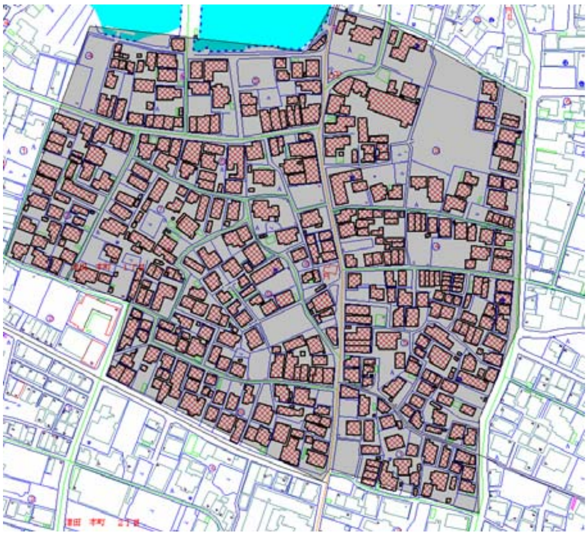
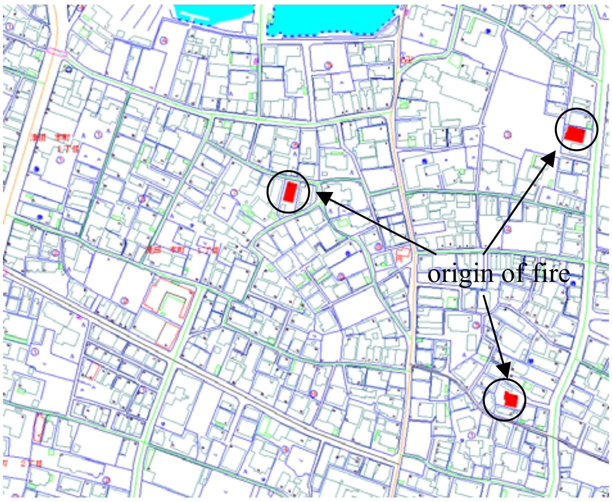


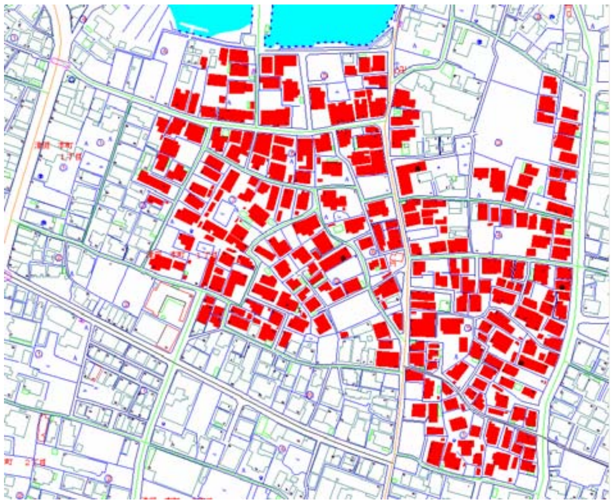
Figure 6 Assignment of analytical area

Figure 8 Analytical model by Petri-net

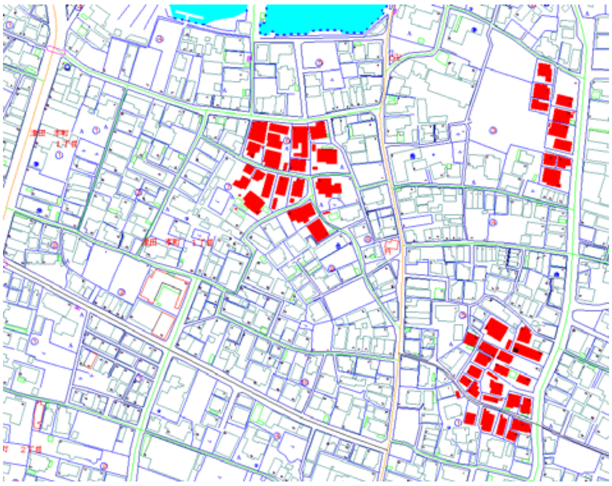
are troublesome and are accompanied by much labor and time as the area of the simulation becomes large. In this study, the system is modified so that the arrangement of places, arcs and transitions can be done automatically in the assigned urban area. The only operation required to create the data is to assign the area by mouse-clicking in the computer display.



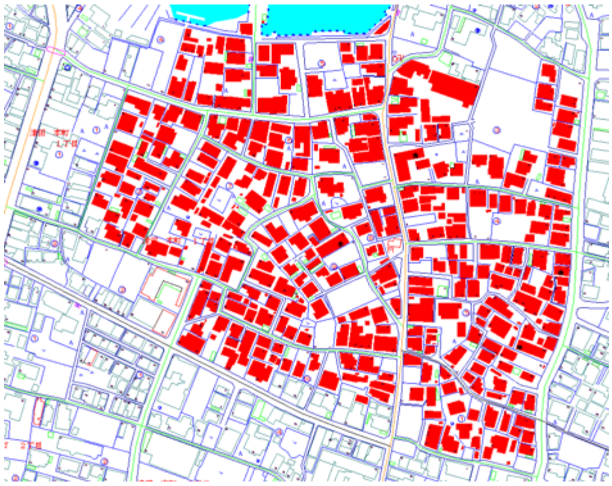
(a) Initial state



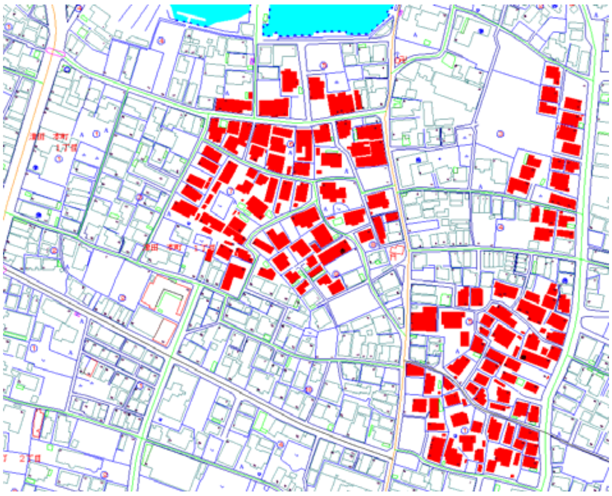
(d) After 180 minutes



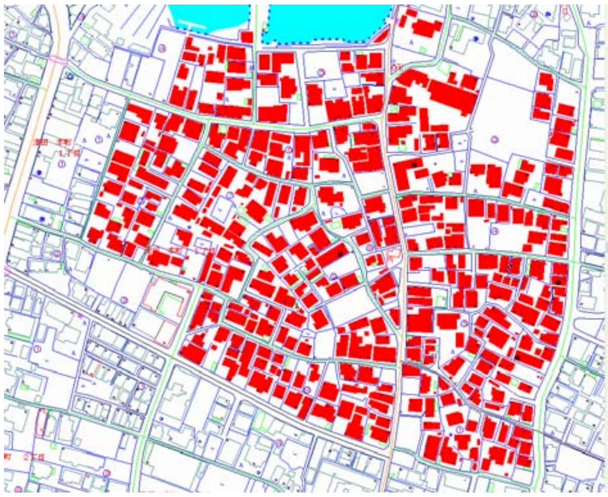
(b) After 60 minutes



(e) After 240 minutes



(c) After 120 minutes



(f) After 300 minutes

Figure 9 Movements of fires by analysis of spreading fires

Let us introduce an example of the automatic creation of the data. Figure 5 shows a part of the residential map. The target for the simulation of spreading fire is shown by the shaded area in Figure 6. The area can be assigned by mouse-clicking on the vertices. Figure 7 shows the analytical models of the houses in the area. Figure 8 shows the analytical models of houses together with inter-house arcs, namely the arcs connecting the places which belong to the different houses. The limit of the length of the inter-house arcs is set to 8 m. Though the arrows of the arcs and transitions are not shown in the figure, the lines connecting the places denote the two-way arcs and the transitions exist in between the places. The weights of the arcs are allocated with the created analytical urban model shown in Figure 8 and the supposed wind velocity, wind direction and seismic intensity.

4. SPREADING FIRE SIMULATION SYSTEM AND NUMERICAL EXAMPLE

An example of the spreading fire analysis is shown in Figures 9. The target area is shown in Figure 6. The conditions in the analysis are supposed as follows.
(1) Wind speed is 4m/sec from east to west.
(2) Seismic intensity is 6 weak in JMA intensity scale.
(3) All of the houses are two-storied wooden.

Figure 9 (a) shows the initial state in which the origins of fires are located. The states at 60, 120, 180, 240 and 300 minutes after fires break out are shown in (b), (c), (d), (e) and (f) in Figure 9, respectively. 499 houses exist in the target area. All of the houses burnt out in 300 minutes after fires had broken out.

5. APPLICATION TO DECISION MAKING OF EXTINGUISHING PRIORITY ORDER

In order to utilize fire fighting capacity, proper decision for the extinguishing priority order based on the prediction of spreading fire is important. In this study, Eqn.5.1 is proposed.

$$B(i) = \sum_{j=1}^{N_f} W(j) \cdot Rank\left(\sum_{k=1}^{N(i)} E(j,k) \right), \quad i = 1,2,\cdots,N_S \tag{5.1}$$

where

N_S ; the total number of burning houses
N_f ; the total number of factors for decision of extinguishing priority order
$W(j)$; weight coefficient for factor (j)
$N(i)$; the total number of houses estimated to catch fire even if the burning house (i) is extinguished
$E(j,k)$; allocated value to the house (k) for factor (j)
$Rank(\cdot)$; extinguishing priority order considering only factor (j)

Then, the extinguishing priority of the burning house (i) is assigned in ascending order of the value of *B(i)*. The decision of extinguishing priority order is demonstrated for the virtual small city shown in Figure 10. The origins of fires are shown by the shaded box. Their identification numbers are shown in the circles. The types of structures for fires, the numbers of households, and the level of importance are shown in Figure 11. The movements of fires after 20 and 60 minutes are shown in Figures 12 and 13, respectively. Progress of the number of the burnt houses is shown Figure 14. Figure 15 shows the extinguishing priority order of the origins of fires which changes with the time, considering such factors as the numbers of houses and households, burnt floor area, level of importance with same weighting. If you wish to minimize the damage in 60 minutes, the extinguishing priority of the houses is high in order of 14, 22, 3 and 30.

CONCLUSIONS

In this study, an automatic modeling system for the analysis of spreading fire in an earthquake using digital residential map is proposed. Based on this system, the order of extinguishing priority can be determined by the comparison of the effect of extinguishments of each building on fire. The major results are as follows.

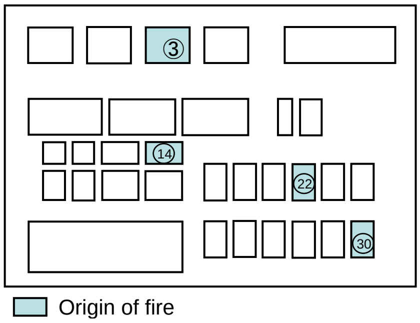


Figure 10 Virtual city and origins of fires

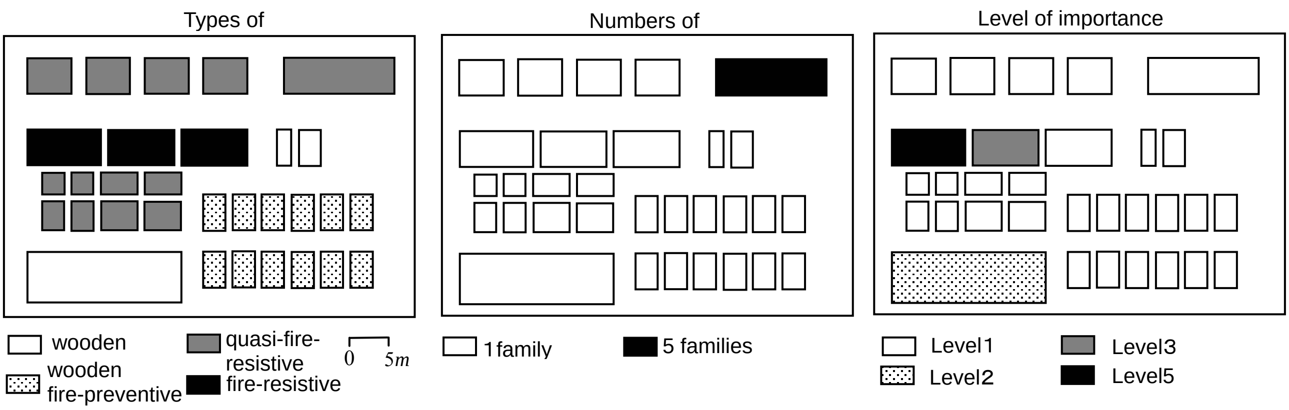


Figure 11 Types of structures, numbers of Households and level of importance in the virtual city

(1) The basic data for the analysis of urban spreading fire in an earthquake can be easily prepared by just assigning the target area in the residential map in the computer display, so that it enables the large-scale simulation of fires.
(2) The algorithm used in this system is helpful to reduce the calculating time, which is short enough to be used in the real-time estimation of spreading fire and the decision making of the extinguishing priority order in the simultaneous occurrence of fires.

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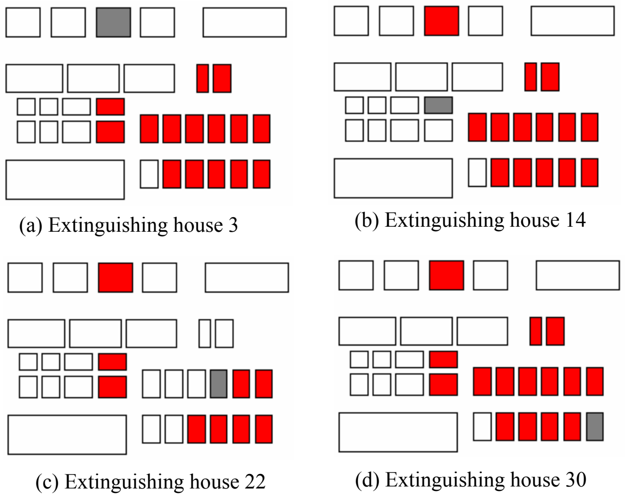

Figure 12 Movement after 20 minutes in the cases of extinguishing each oringin of fires

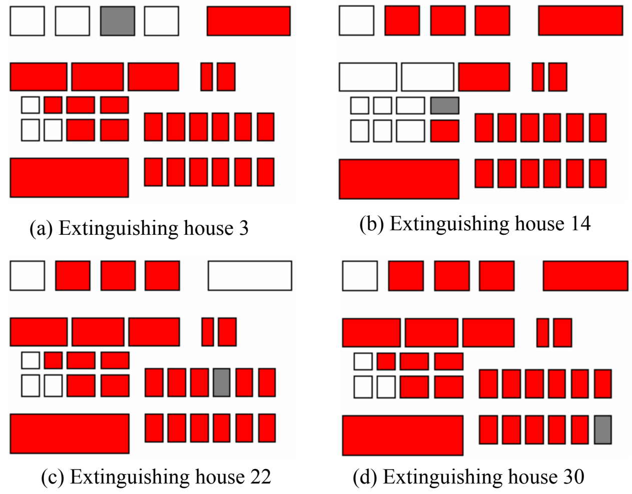

Figure 13 Movement after 60 minutes in the cases of extinguishing each oringin of fires

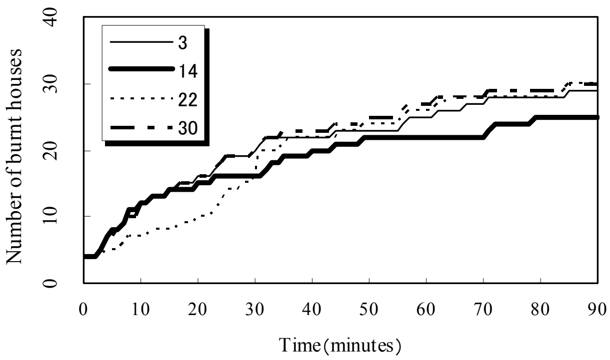

Figure 14 Progress of the number of burnt houses in the case of extinguishing each origin of fires

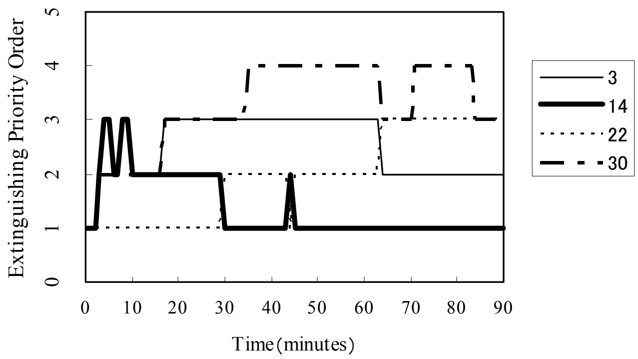

Figure 15 Shift of extinguishing priority order

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