Development of Automatic Modeling System for Simulation of Urban Spreading Fire in an Earthquake

Osamu Tsujihara [1] , Kazuhiro Terada[2] and Tsutomu Sawada [3]

Abstract: 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 the digital residential map is proposed. Almost all the data, which are necessary for the simulation of urban spreading fire in an earthquake, are made automatically and written in the files by just only assigning the target area in the map. The techniques used in the automatic modeling system are introduced. Using this system, a simulation of urban spreading fire is demonstrated.

Keywords : *automatic modeling, simulation, spreading fire, earthquake, urban area*

1. INTRODUCTION

Perfect fire fighting can not be expected under the special circumstances such as urban fire in an earthquake. 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.

Formulas of spreading velocities of fire inside a house and between neighboring houses were proposed based on the researches of the past fires and physical experiments. Hamada's formula[1)] of spreading velocity of fire is well known and had been used for the fire of wooden houses. Some other formulas were proposed for the wooden fire-preventive and quasi-fire-resistive types. TFD (Tokyo Fire Department)[2)] proposed a new formula, which is called "Toshoshiki 97". The accuracy of spreading velocity of fire was remarkably improved through the research of damages in the fires in 1995 Hyogo-ken Nanbu Earthquake. The influence of the collapse of houses was also reflected. Later, the TFD's formula was modified, so that fire-resistive and quasi-fire-resistive types of houses can be managed. It is called "Toshoshiki 2001". This is one of the most reliable formulas of spreading velocity of fires.

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. Yano, *et al*.[3)] applied their original formula of spreading velocity of fire to the simulation of the fire in Kobe in 1995 Hyogo-ken Nanbu Earthquake. Sekizawa[4)], *et al*. utilized the 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*.[5,6)] also proposed the system to simulate urban fire in an earthquake in which the digital residential map was used. Later, Tsujihara, *et al*.[7)] modified the system by introducing the Perti-net (: e.g. Reising[7)]), 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*.[9)] confirmed the validity of the system through the simulation in the burned area in Hyogo-ken Nanbu Earthquake.

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However, there are two problems in the system which Tsujihara, *et al.*[7] proposed. The first problem is that the shape of the top view of a building is limited to quadrilateral. The second problem is that it requires much time and labor in the process of making the analytical model since a large part is done manually. Some prior technical knowledge is also required to do so.

Recently, the evaluation of performance for the urban disaster prevention has been regarded as more and more important. Simulation of urban spreading fires has also been more and more required as a useful method to evaluate the safety against fires. Some tools were proposed for the simulation of urban spreading fires including the Tsujihara's system[7]. In the application of a tool, the primary concern is the ease of making analytical model of the urban area.

The objective of this study is to develop the Tsujihara's simulation system[7] 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 created and written in the corresponding files by just assigning the target area on the residential map in the computer display. No technical knowledge is required. In this system, the problem that the shape of the top view of a building is limited to quadrilateral is also overcome. This system is developed with VB (Microsoft Visual Basic). Active Map[10] is used as the engine to show the residential map (Zenrin[11] Zmap-Town 2) in the computer display.

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

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 TDF formula, is allocated to the weight of each input arc.

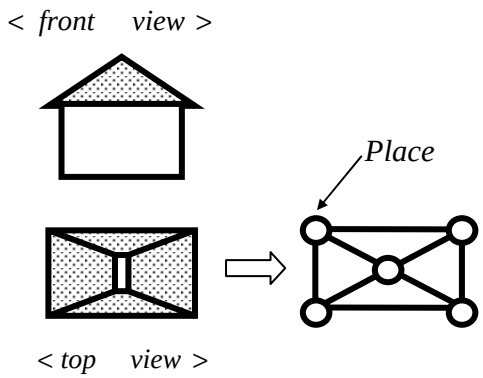

Figure 1 Modeling of a House

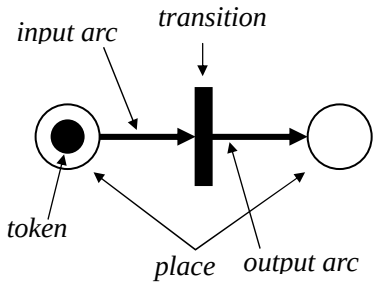

Figure 2 Petri-net

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 TDF 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. Readers may refer to the paper[7] for further details.

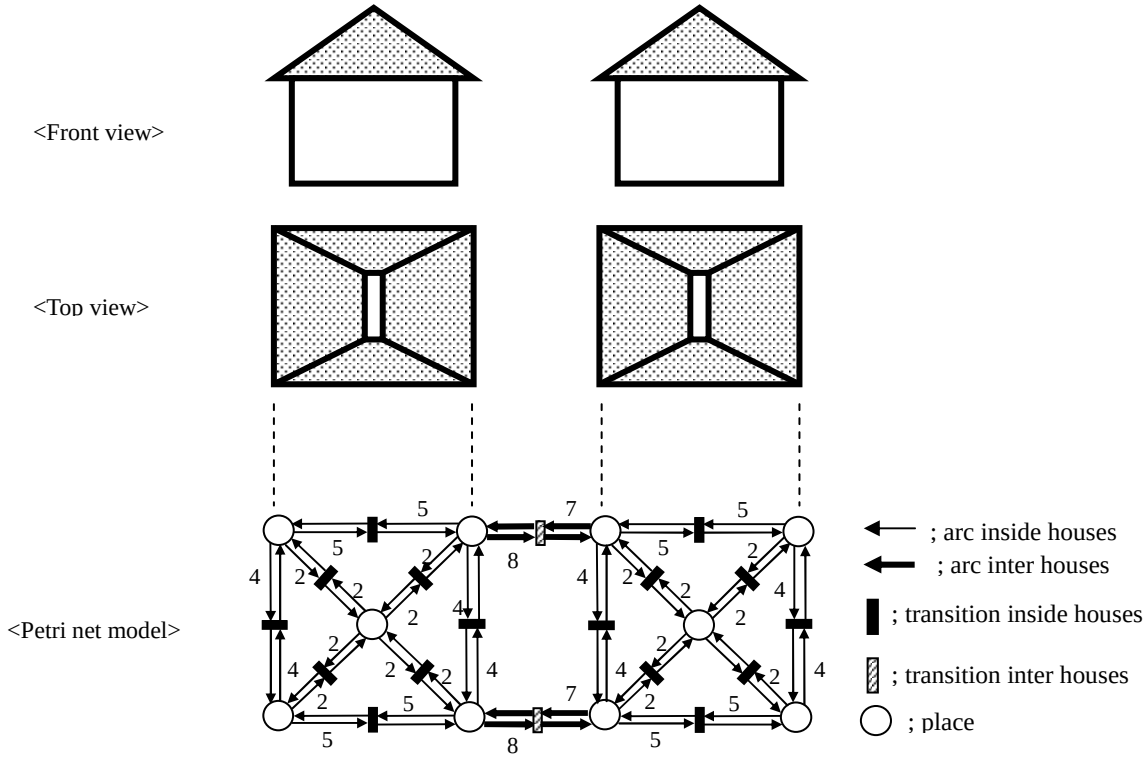

Figure 3 Petri-net Modeling for Simulation of Spreading Fire

3. AUTOMATIC DATA CREATION OF ANALYTICAL MODEL

In the system proposed by Tsujihara *et al.* [7], 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 are troublesome and 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.

Let us introduce an example of the automatic creation of the data. Figure 4 shows a part of the residential map. The target for the simulation of spreading fire is shown by the blue shaded area in Figure 5. The area can be assigned by mouse-clicking on the vertices. Figure 6 shows the analytical models of the houses in the area. Figure 7 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 7 and the supposed wind velocity, wind direction and seismic intensity. The techniques to create the data of the analytical model are shown in the followings.

(1) Modeling a House

The places are set at the vertices and the center of the plane shape of each house. The places are numbered serially, and their coordinates are automatically read from the residential map and written in the Excel file as shown in Table 1. The arcs are also set at between the corresponding places and the place numbers of both ends for each arc as well as its type is written in the file as shown in Table 2. The type is either 1 or 2 which denotes whether the arc is

Figure 4 Residential Map

Figure 5 Assignment of Analytical Area

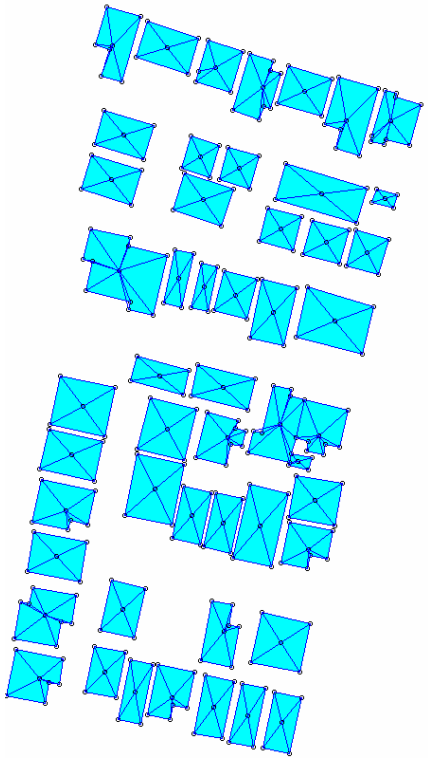

Figure 6 Model of houses

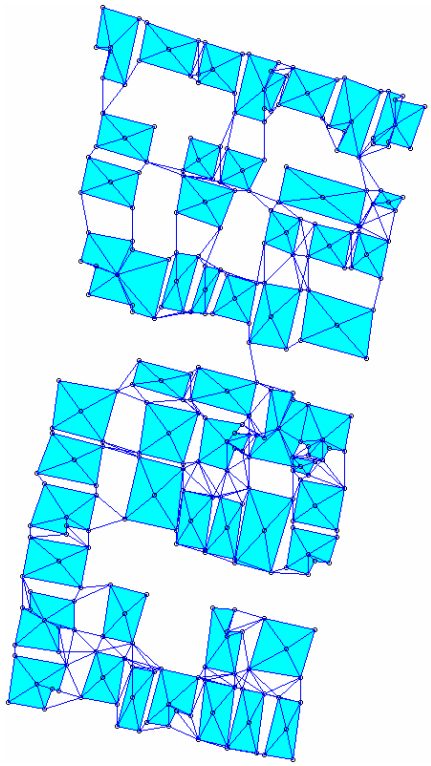

Figure 7 Analytical Model by Petri-net

inside a house or inter house, respectively. The wooden, wooden fire-preventive, quasi-fire-resistive and fire-resistive types are denoted by 1, 2, 3 and 4, respectively. The fire-resistive level is set only for the quasi-fire-resistive and fire-resistive types. The

Table 1 Example of Data File of Places

No.	Longitude	Latitude
1	134.5856083	34.06056
2	134.5856611	34.0605475
3	134.5856372	34.06047583
4	134.5855872	34.06048639

Table 2 Example of Data File of Arcs

No.	Input Place No.	Output Place No.	Type
1	1	2	1
2	2	3	1
3	3	4	1
4	4	5	1
5	5	6	1

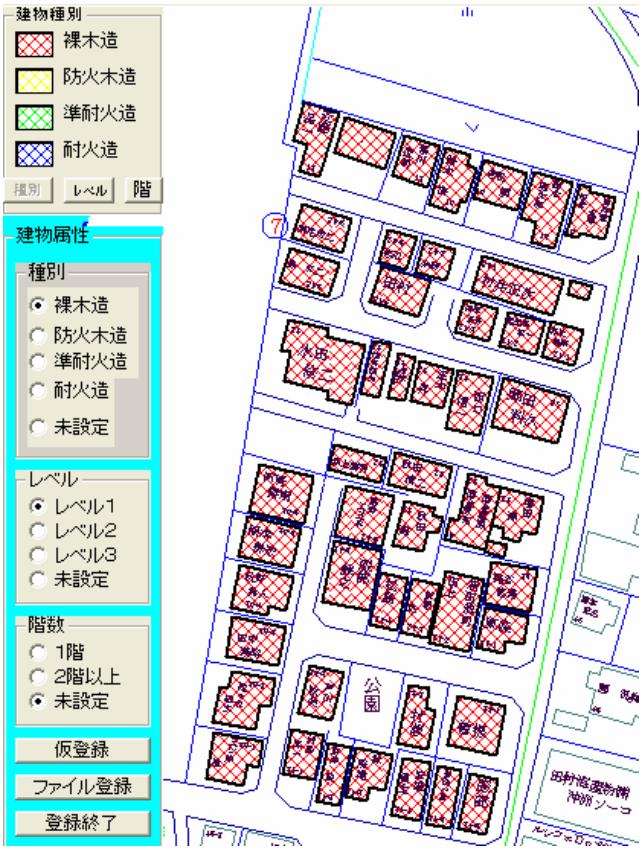

Figure 8 Subsystem for Editing the Attribute Data of Houses

transitions are also automatically set at between the places which are linked by the input and output arcs. The numbers of the places that belong to each house as well as the type of house, fire-resistive level, stories, link codes and the total numbers of the places are written in the file as shown in Table 3. Since the attribute data on the type and story of each house can not be identified from the residential map, these data are written with the help of the subsystem which is shown in Figure 8. All of the data are written in Microsoft Excel, which can be edited directly.

（2）Method for creation of inter-house arcs and transitions

The arcs, including transitions, from a place are basically set to all places that belong to other houses as shown in Figure 9. Then, the enormous number of arcs and transitions are included in the model, which wastes the computing time. The following 4 cases are excluded from setting the arcs and transitions.

① The distance between the centers of the houses is over the limit.
② The distance between the places is over the limit.
③ The arc and transition have already been set.

Table 3 Example of Data File of Attribute of Houses

No.	Type	Level	Story	Link code	Verti-ces	Place No.									
						1	2	3	4	5	6	7	8	9	10
1	1		2	1-82-4-58130816-1045	9	1	2	3	4	5	6	7	8	9	10
2	1		2	1-82-4-58130816-1047	4	11	12	13	14	15					
3	1		2	1-82-4-58130816-1064	4	16	17	18	19	20					
4	1		2	1-82-4-58130816-135	6	21	22	23	24	25	26	27			

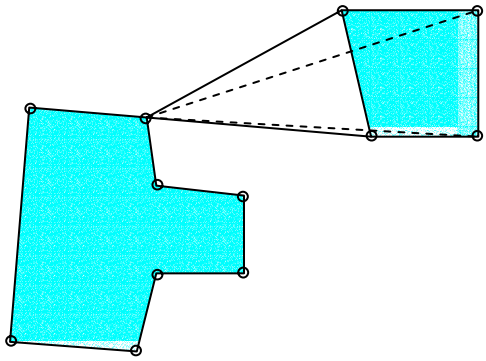

Figure 9 Candidate Arcs from a Place to Those of Other Houses

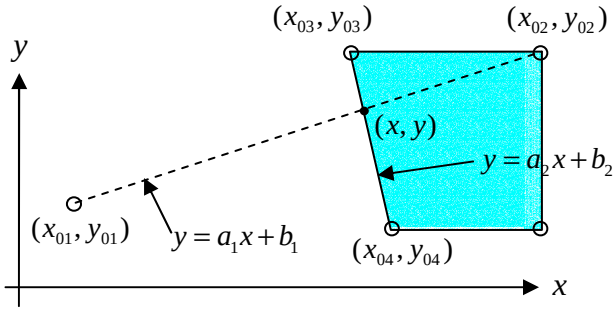

Figure 10 Arc Crossing the Polygon of a House

④ The line, which links two places, crosses the polygon of any house.

Among these 4 cases, the first 3 case can be managed easily. The details of only the case ④ is shown in the followings.

Suppose that the line, which links the places of different houses, crosses the polygon of a house as shown in Figure 10. The equations of the lines which have the intersection can be shown by

$$y = a_1 x + b_1$$
$$y = a_2 x + b_2$$

where a_1, b_1, a_2, b_2 are obtained by

$$a_1 = \frac{y_{02} - y_{01}}{x_{02} - x_{01}}$$
$$b_1 = y_{01} - a_1 x_{01}$$

$$a_2 = \frac{y_{04} - y_{03}}{x_{04} - x_{03}}$$
$$b_2 = y_{03} - a_2 x_{03}$$

The coordinates of the intersection (x,y) can be obtained as

$$a_1 x + b_1 = a_2 x + b_2$$
$$(a_1 - a_2)x = b_2 - b_1$$
$$\therefore x = \frac{b_2 - b_1}{a_1 - a_2}$$
$$y = a_1 \frac{b_2 - b_1}{a_1 - a_2} + b_1$$

If the coordinates of the intersection (x,y) satisfy one of the following relations 1)～3), the line, which links two places, is judged to cross the polygon of a certain house.

It is supposed that $x_{01}<x_{02}$, $x_{03}<x_{04}$, $y_{01}<y_{02}$, $y_{03}>y_{04}$, as shown in Figure 10 in the following explanation.

1) In the case of $x_{01} \neq x_{02}$,

$x_{01} < x < x_{02}, x_{03} < x < x_{04}, y_{01} < y < y_{02}$ and

$y_{04} < y < y_{03}$ are simultaneously satisfied.

2) In the case of $x_{01} = x_{02}$,

$x_{03} < x < x_{04}$, $y_{01} < y < y_{02}$ and $y_{04} < y < y_{03}$ are simultaneously satisfied.
where

$$x = x_{01}$$
$$y = a_2 x_{01} + b_2$$

3) In the case of $x_{03} = x_{04}$,

$x_{01} < x < x_{02}, y_{01} < y < y_{02}$ and $y_{04} < y < y_{03}$ are simultaneously satisfied.
where

$$x = x_{03}$$
$$y = a_1 x_{03} + b_1$$

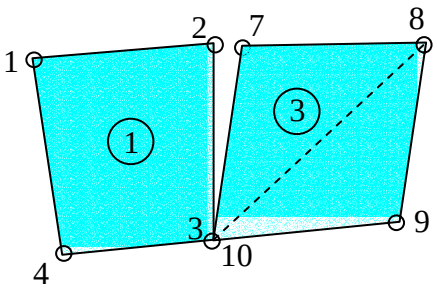

Figure 11 Place of the Input Arc is Held by Another House in Common

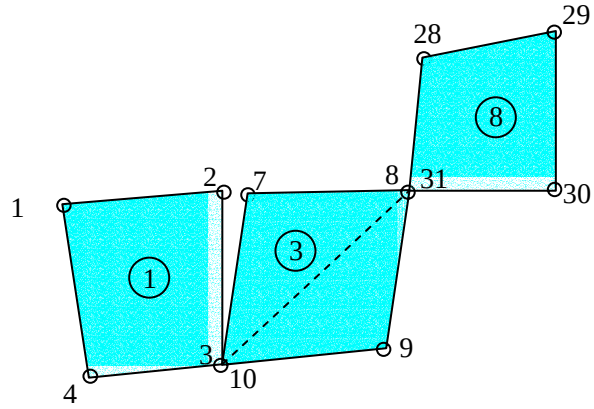

Figure 12 Both of the Places of the Input and Output Arcs are Held by Another House in Common

The action, which is mentioned above, is called "Check_Link 1".

According to the action, there are the cases in which arcs and transitions are set wrongly if two or more houses hold the places whose coordinates (x,y) are identical. From the top view, these houses are regarded to hold the same place. The examples and the actions to the cases are shown in the followings.

a) The place of the input arc is held by another house in common.

The places 3 and 10 belong to the houses whose numbers are 1 and 3, respectively in Figure 11. These places have the identical coordinates. The line from the place 3 toward 8 is regarded not to cross the polygon of the house 3 according to the action "Check_Link 1". In such the case, the arcs and transitions from the place 3 toward the places of the house 3 are not set except for toward the place 10. Though the distance of the places 3 and 10 is 0, the arcs and transition are required to be set because the fire spread from one to another. The action, which is mentioned above, is called "Check_Link 2".

b) The place of the output arc is held by another house in common.

If you look at a) from the opposite side, the line from the place 8 toward 3 is also regarded not to cross the polygon of the house 3 . In such the case, the arcs and transitions are not set. The action, which is mentioned above, is called "Check_Link 3".

c) Both of the places of the input and output arcs are held by another house in common.

The places 3 and 10 belong to the houses whose numbers are 1 and 3, respectively in Figure 12. The places 8 and 31 belong to the houses whose numbers are 3 and 8, respectively. The line from the place 3 toward 31 is regarded not to cross the polygon of the house 3. In such the case, the arcs and transitions are not set. The action, which is mentioned above, is called "Check_Link 4".

Figures 13～18 shows the analytical models in which these actions are taken place. First, the action of "Check_Link 1" should be taken place because it cut much computing time. Thus created data of the arcs and transitions are added to the file which is shown in Table 2.

（3）Calculation of weights of input arcs

After the layout of places, arcs and transitions, the weights of the input arcs are calculated for the given wind speed, wind direction and seismic intensity, and the required data are written in the file as shown in Table 4. The weight corresponds to the spreading time of fire from the input to output arcs. In the calculation of spreading fire by Petri-net algorithm, the weights are rounded to the nearest integral number. The weights of all the output arcs are fixed to 1.

4. SPREADING FIRE SIMULATION SYSTEM AND NUMERICAL EXAMPLE

The flow of operations in building the analytical model, simulation and graphic output of the movements of spreading fire are shown in Figure 19. In the conventional system[7], a part or all of such the files as "Coordinate of places", "Attribute of arcs" and "Attribute of houses" are created by mouse-clicking each house. In this system, almost all the data, which are required in the simulation of spreading

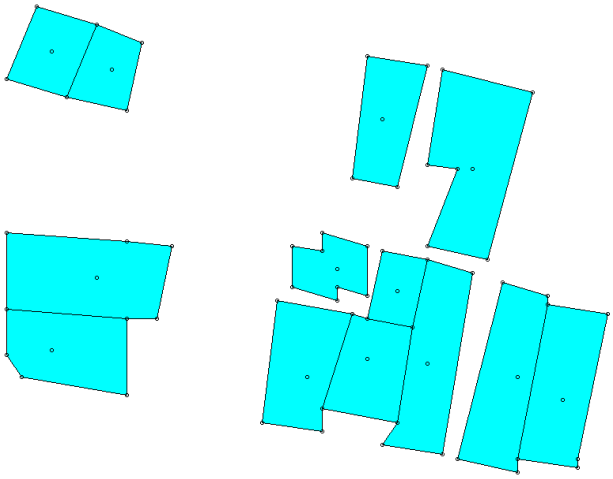

Figure 13 Frames of Houses

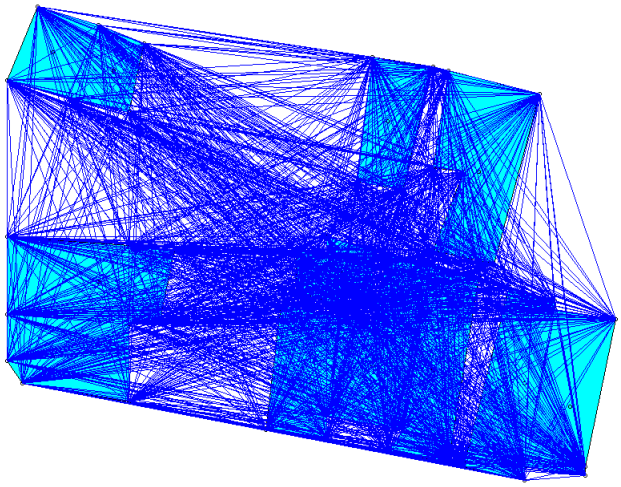

Figure 14 Arcs without Any Actions for Reduction of Useless Arcs

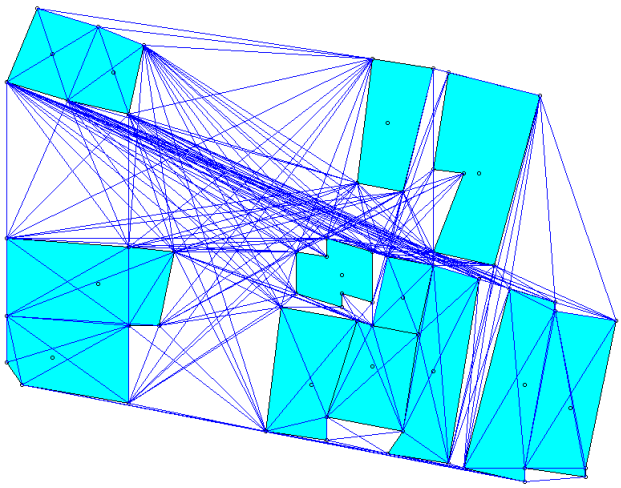

Figure 15 Arcs in the Case Applying Action "Check_Link1"

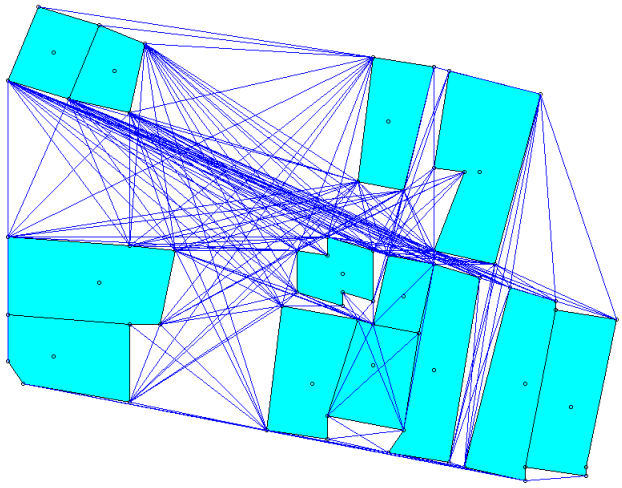

Figure 16 Arcs in the Case Applying Action "Check_Link 1 ,2 & 3"

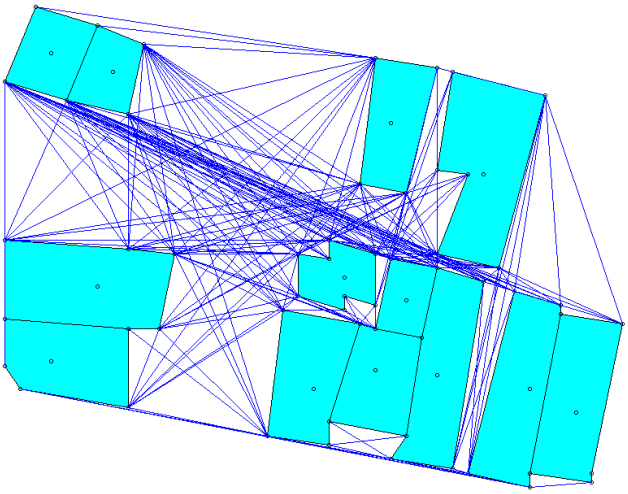

Figure 17 Arcs in the Case Applying Action "Check_Link 1 ,2, 3 & 4"

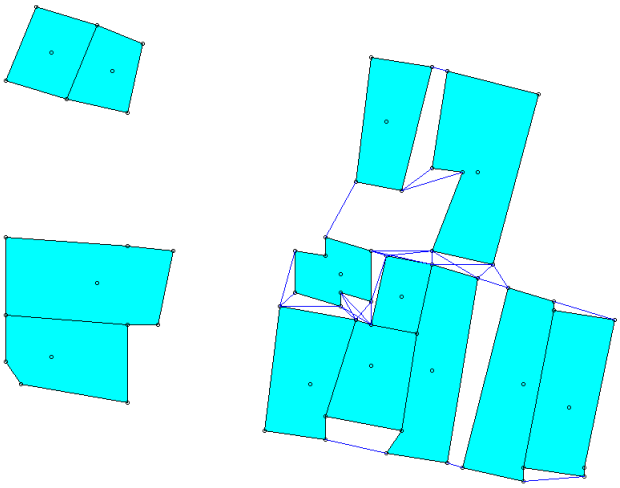

Figure 18 Arcs in the Case Applying Action "Check_Link 1 ,2, 3 & 4" and the Limit of Distance between Places (6m)

Table 4 Example of Data File of Weights of Input Arcs

No.	No. of Input Place	No. of Output Place	Type	Distance (m)	Spreading Time (minute)
1	1	2	1	6.01	6.92
2459	2	1	1	6.01	6.92
2	2	3	1	13.69	15.77
2460	3	2	1	13.69	15.77
3	3	4	1	1.07	1.23
2461	4	3	1	1.07	1.23

fires, are created by just assigning the area on the residential map by mouse-clicking in the computer display. The houses which are the origins of fires can be selected by mouse-clicking on them. Then, the required data in the simulation are automatically written in the file.

An example of the spreading fire analysis is shown in Figures 20 and 21. The wind from east to west whose speed is 4m/sec and the seismic intensity of 5 weak are supposed. All of the houses are supposed to be wooden and 2 story. Figure 20 shows the initial state. The states after 30, 60, 120 and 180 minutes are shown in (a), (b), (c) and (d) in Figure 21, respectively. The fires spreading from the northern origin stop about 60 minutes later. On the other hand, the fires spreading from the southern origin continue to spread after 60 minutes and take over 180 minutes to stop. In this simulation, the maximum weight of an input arc is set to 60. So that if the required spreading time between arbitrary two places exceeds 60 minutes, the fire

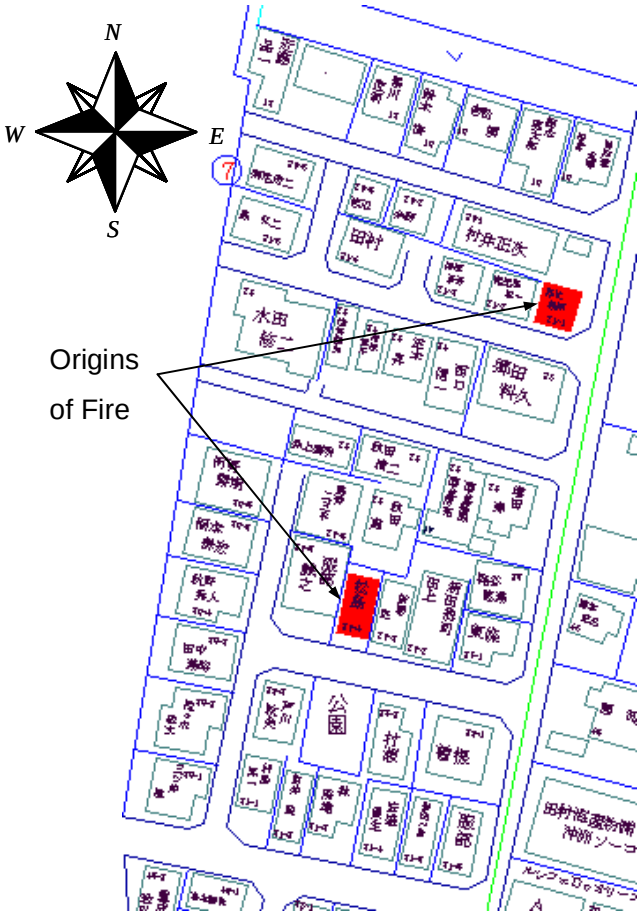

Figure 20 State at Break out of Fires

does not spread along the arc. This is the reason why the fires do not spread to the houses in the northern block.

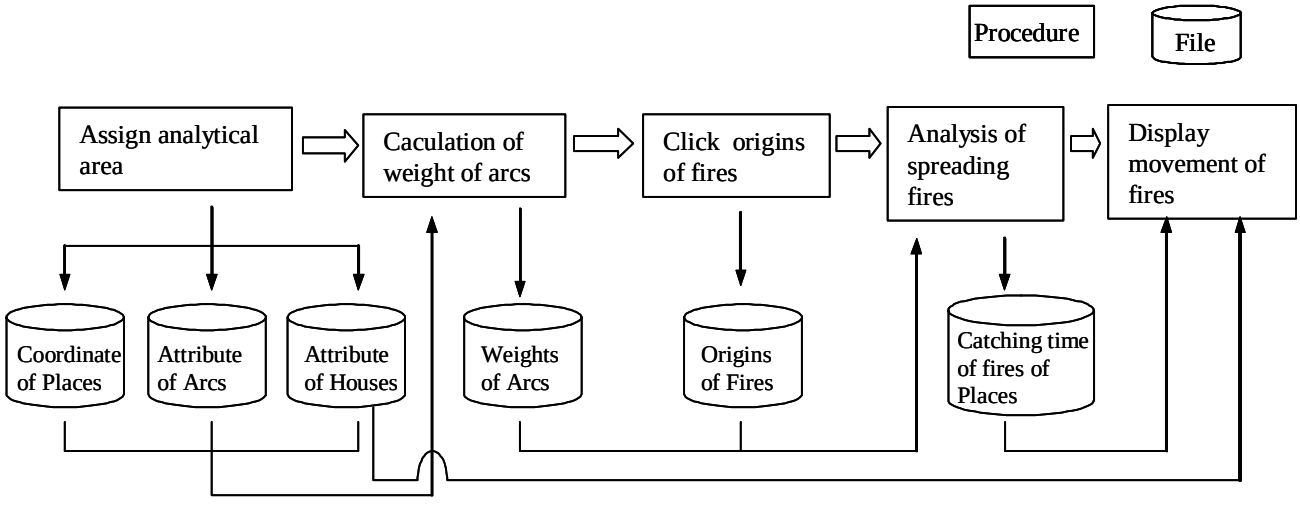

Figure 19 Files of Data and Procedures for Spreading Fire Analysis

(a) After 30 minutes

(b) After 60 minutes

(c) After 120 minutes

(d) After 180 minutes

Figure 21　Movements of Fires by Analysis of Spreading Fires

The fires of the south block come by way of the eastern block, not directly from the block which includes one of the origins of fire, because, as shown in Figure 7, the arcs from the houses near the southern origin of fire to ward the houses in the south block are not set. The limit of the length of an arc is set to 8 m in this simulation.

5. CONCLUTIONS

The system is developed to create the data of the analytical model for the calculation of the urban

spreading fires, which is based on the TFD formula of spreading velocity “Toshoshiki 2001”, by the simple manner. This system will not only set you free from the complicated and troublesome labor of data input but also enable the large-scale spreading fire simulation.

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