Stochastic Transition of Fire-prevention Performance of Urban Area

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Abstract: The aim of this study is to analyze the tendency of building renewal in order to understand the fire prevention performance of the Tokyo metropolitan area. To this end, firstly, the Tokyo metropolitan area was divided into small areas of 250,000 square meters, and the following stochastic transition matrix of each small area was estimated,
1. Stochastic matrix of state transition between the building use types,
2. Stochastic matrix of state transition between the structures of buildings.
Secondly, the converged state of each small area was estimated with a Markov chain model. Finally, small areas where fire prevention performance will change for the better/constant/worse were pointed out from their converged states. The results suggest that in small areas where percentage of housing and commerce are increasing, the fire prevention performance will become worse.

1. INTRODUCTION

A number of cities in Japan have been involved in huge earthquake disaster, in which thousands of people died. Most of them were victims of fires, because the urban area holds a large number of flammable wooden buildings. Therefore, in order to mitigate the urban earthquake disaster, we need to understand the tendency of building renewal in those areas, and to reduce flammable wooden buildings and to increase fire prevention or fire-resistant buildings.

In this study, the transition tendency of building structure and building use type were analyzed, and areas with a possibility of getting better/ constant/ worse of the fire prevention performance in the future are clarified.

For this purpose, firstly, the Tokyo metropolitan area was divided into small areas, each of which had an area of 250,000 square meters, and following stochastic transition matrix of each small area was estimated,

1. Stochastic matrix of state transition of the building use types (P_u),
2. Stochastic matrix of state transition of the structure of buildings (P_s).

Secondly, the converged state of each small area was estimated with a Markov chain model, and the tendencies of changes of the fire prevention performance of each small area were clarified. Finally, small areas were classified into the areas where fire-prevention performance will change for the better/constant/worse, and the characteristics of stochastic transition matrix of each group were compared.

2. METHOD

2.1 How to estimate state transition

2.1.1 Stochastic transition model

A stochastic transition model is a kind of a Markov chain model assuming that the state of a city will change under the influence of its transition probability and its state of just before the time.

In previous studies, Kim (1990), Yoshikawa et al. (1990) and Ishizaka (1992a, 1992b) have tried to analyze the state transition of land use using this model. Since stochastic transition model was detailed in the previous studies, an outline is described here.

$X(t)$ is a state vector of the state of time t. The element of $X(t)$ is $x_i(t \mid t \geq 0, i = 1,\dots,m)$ which is the percentage of several kinds of categories i ,

$$X(t) = \begin{bmatrix} x_1 \\ \vdots \\ x_m \end{bmatrix}, \quad x_1(t) + \cdots + x_m(t) = 1, \quad 0 \leq x_i(t) \leq 1.$$

In addition, p_{ij} is the rate of area whose state is i at certain time and is j at the next time, and p_{ij} satisfies following equation,

$$p_{1i} + \cdots + p_{mi} = 1, \quad 0 \le p_{ij} \le 1.$$

The stochastic transition matrix P is a matrix placed in m rows and m columns whose element (i, j) is p_{ij},

$$P = \begin{bmatrix} p_{11} & \cdots & p_{1j} & \cdots & p_{1m} \\ \vdots & \ddots & & & \vdots \\ p_{i1} & & p_{ij} & & p_{1m} \\ \vdots & & & \ddots & \vdots \\ p_{m1} & \cdots & p_{mj} & \cdots & p_{mm} \end{bmatrix}.$$

When the state vector X (0) is given, state X (t) is estimated as the following formula,

$$X(t) = PX(t-1) = \cdots = P^t X(0).$$

In this study, a stochastic transition matrix P was estimated from the following two data.

1) Data of the building structure in 1991 and 1996.
2) Data of the building use in 1991 and 1996.

2.1.2 The converged state of transitions

Fire prevention performance of the converged state of stochastic transition should show the tendency of change. In this research, this converged state was estimated as follows.

When the Eigen equation of the stochastic transition matrix P does not have a multiple root, the state vector of each area is converged on the static state which equals to the eigenvector corresponding to eigenvalue 1.

2.2 Evaluation method of fire prevention performance

The fire prevention performance was evaluated by an estimation of spreading velocity of fire.

The estimation method of spreading velocity of fire is divided roughly into a block unit model and an one-building unit model. Hamada's expression (Hamada, 1951) is a typical former model. Although this expression has a theoretical difficulty, it suits the past conflagration data well and it was used in many studies, such as Okada (1979). In addition, there are many expressions which based on the Hamada's expression, in the studies, for examples, by Tokyo Fire Department, by Horiuchi (1972), and by Fujita (1973).

On the other hand, the one-building unit model based on stochastic fire spreading to the next building were used by Aoki (1976) and Itoigawa et al. (1984). According to this model, the spreading velocity of fire is estimated by computer simulation, for example by Tokyo Fire Department.

In order to understand how the spreading velocity of fire changes, the index of fire prevention performance (index α) estimated from Hamada's study has been used as the simplest way. The index is indicating the spreading velocity of fire in a city area. This index changes depending on the structures of buildings in a small area. When the relative compositions of nakedness wooden buildings, fire prevention buildings, and fire-resistant buildings are a, b and c (a + b + c = 1), the index is given by the following formula,

$$\alpha = (a+b)^2 \Big/ (a + \frac{b}{0.6}) .$$

The area where the above-mentioned index is smaller is considered to be an area where a fire does not spread easily.

In addition, the index is defined as follows. When all the buildings are nakedness wooden, it is set to 1. When all the buildings are fire prevention buildings, it is set to 0.6. When all the buildings are fire-resistant, it is set to 0 (Figure 1).

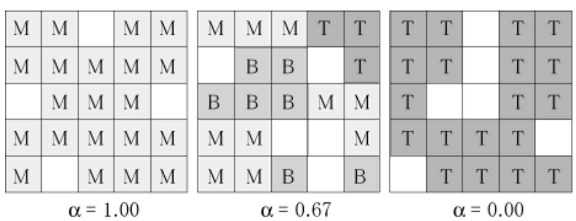


Figure 1: An example of index of fire prevention performance (α)
(T : fire-resistant, B : fire prevention, M : nakedness wooden)

3. DATA TO BE USED

3.1 Preparation procedure of data

The region for this study is a ward of Tokyo (Figure 2). The building data of the Tokyo city planning geographical information system were used as original data. Preparation procedure of the data is as follows.

1. Classification of building structure and building use type

2. Making mesh-data
3. Set up of the aggregation range

Hereafter, each stage will be explained.

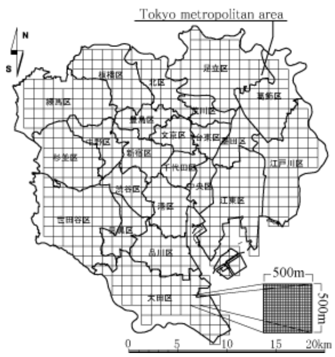


Figure 2: Ward area of Tokyo

3.2 Classification of building structure and building use type

Each building polygon of the original data has following property information such as area, peripheral length, number of stories, number of underground stories, the building structure code, the land-and-building use code, and the gross floor space conversion code. In this study, building structure code and land-and-building use type code were used (Figure 3). Although these codes were classified into six types and thirty types in the original data, they were re-classified into following three types and four types, respectively.

Building structure type:
- Wooden building (W)
- Fire prevention building (FP)
- Fire-resistant building (FR)

Building use type:
- Housing (H)
- Commercial building (C)
- Public building (P)
- Agricultural or Industrial building (AI)

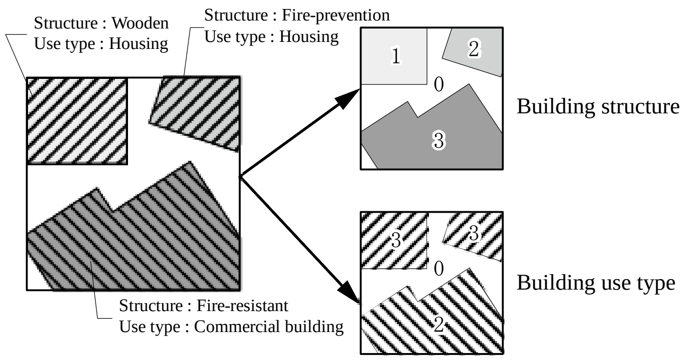


Figure 3: Classification of building structure and building use type

3.3 Making mesh-data

Each building polygon of the original data also has the information of the position and the shape of buildings. Since this study aims at understanding the fire prevention performance of a city area roughly, it was converted into the mesh data of 10 m square on a side according to the procedure of Figure 4.

3.4 Set up of the aggregation range

In order to analyze the local difference in a state transition tendency, the region was divided into small areas of 500m x 500m as shown in Figure 2, and a stochastic transition matrix and a converged state were estimated separately.

Since the estimated result for each small area may be changed by set up of an aggregation unit, only a general tendency was obtained.

4. THE SITUATION TRANSITION OF BUILDING STRUCTURE

Based on the above preparation, in this section, the relative spreading velocity of fire in converged state was estimated, and the distribution of small areas whose fire prevention performance changes for the better/constant/worse in the future were examined.

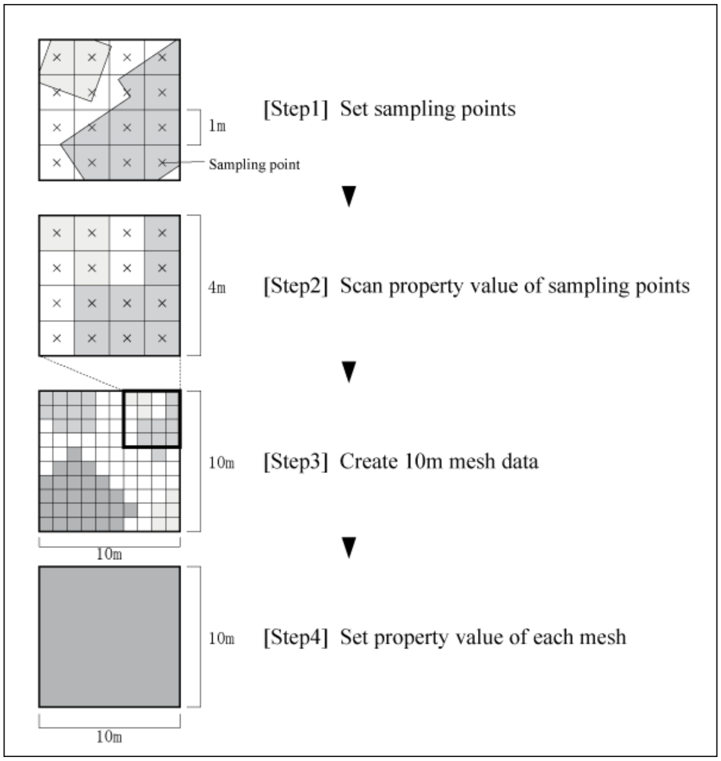


Figure 4: Making mesh data

4.1 Relative composition of building structures in the converged state

The stochastic transition matrix P_s about the building structure of each small area was estimated from the data described in the preceding section. The eigenvector corresponding to the eigenvalue 1 of this P_s was calculated, and the converged state was estimated. The following results were obtained.

4.1.1 Relative composition of the building structures of the whole region

The percentage of a fire-resistant building for the whole region increased from 12.6% in 1996 to 28.2% at the converged state. On the other hand, the percentage of wooden buildings, fire prevention buildings, and void spaces area decreased. Especially the relative composition of void spaces decreased greatly to 61.5% from 73.8% (Table 1). Therefore, if the tendency of the change continues indefinitely in the city area at a converged state, the relative composition of fire-resistant buildings will increase eventually.

Table 1: Relative composition of the building structures for the whole region

	1996	Converged state
Void space	73.8%	61.5%
Wooden building	3.1%	1.0%
	(11.9%)	(2.6%)
Fire prevention building	10.5%	9.3%
	(40.1%)	(24.2%)
Fire-resistant building	12.6%	28.2%
	(48.0%)	(73.2%)
Total	100%	100%
	(100%)	(100%)

4.1.2 Relative composition of the building structures of each small mesh

Figure 5 shows the relative compositions of the building structure except for void space by the color thickness of a mesh. A deep-colored mesh indicates a high relative composition of the corresponding structure. According to this Figure, although the relative composition of the wooden buildings was already low in 1996, there will be further increase in number of areas with no wooden building at the future converged situation. Moreover, as a whole, the relative composition of the fire prevention buildings will also decrease, and it is possible to find some districts, in which the decrease are remarkable, especially in the northeast and the northwest parts. On the other hand, the relative composition of the fire-resistant building will increase. There are many deep-colored meshes even in the district distant from the center of Tokyo at the converged state, although it was already concentrated around the littoral district or at the center of Tokyo in 1996.

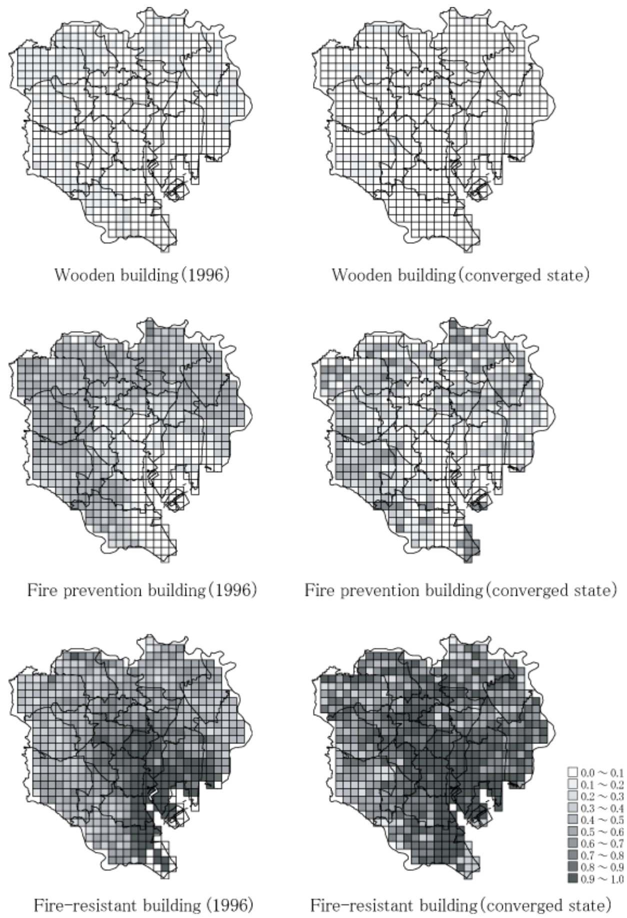


Figure 5: Distribution of different building structures

4.2 Fire prevention performance at converged state

Then, the index α at the estimated converged state was calculated, and the changes in the fire prevention performance were analyzed. As discussed below, the index of converged state (α_{∞}) was compared with that of 1996 (α_{1996}).

4.2.1 Fire prevention performance of the whole region

The arithmetical mean of the relative fire spreading velocity of all the small districts has been improved to 0.18 at the converged state from 0.34 in 1996 (Figure 6).

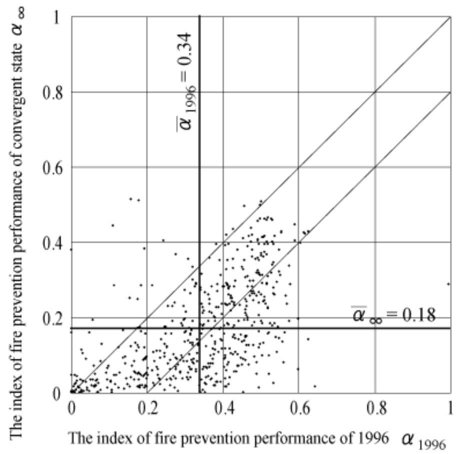


Figure 6 : Scatter plot of the index α

4.2.2 Fire prevention performance of each mesh

Figure 7 shows the index (α_{∞} and α_{1996}) of each mesh, and a deep-colored mesh indicates a high index. In both of 1996 and a converged state, the districts with low index are concentrated at the center of Tokyo, but at the converged state, it is distributed even larger area. Therefore, the city area where a fire does not spread easily can be expected to expand to the limb partes in the future.

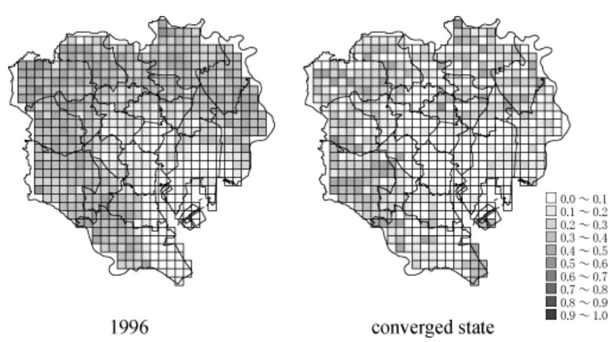


Figure 7 : The index α (α_{1996} and α_{∞})

Moreover, Figure 8 shows the inequality between both indices ($\alpha_\infty - \alpha_{1996}$). A deep-colored mesh indicates the district where the index will increase, in other words, will change to the worse greatly. It is considered that the index will become worse in the future in a littoral district or the center of Tokyo.

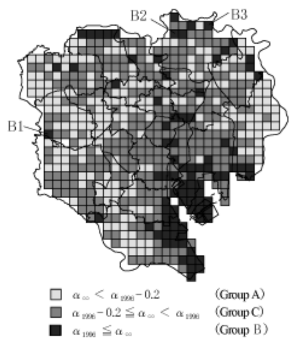


Figure 8 : The inequality of α_{1996} and α_∞

5. COMPARISON OF AREAS WITH DIFFERENT TRENDS FOR FIRE PREVENTION PERFORMANCE

The differences in the state transition probability matrix of each small area is a factor which causes the difference in the relative spreading velocity of fire. In order to understand the relationship between the trend of a fire prevention performance and the characteristics of a state transition, small areas were sorted into the following three groups according to a trend of index α.

Group A: The areas for which the index at the converged state is improved greatly compared with 1996
Group B: The areas where the index at the converged state become worse compared with 1996
Group C: The areas for which the index at the converged state is improved slightly compared with 1996

5.1 Relative compositions of buildings

The relative compositions of the building constructions according to the groups are shown in Table 2 and Table 3. The values in the parenthesis are the composition except for void space. As compared with other two groups, Group B has a larger relative composition of void spaces, such as an unused land, and its composition of the fire prevention building is lower. And these are areas where the rate of housing is low and the rate of agricultural and industrial building is high.

Table 2 : Relative compositions of building structures of the whole region

Structure	Group A	Group B	Group C
Void space	72.2%	81.1%	72.2%
Wooden building	3.3%	1.5%	1.9%
	(11.8%)	(8.0%)	(7.0%)
Fire prevention building	12.9%	6.2%	10.1%
	(46.5%)	(32.8%)	(36.1%)
Fire-resistant building	11.6%	11.2%	15.8%
	(41.7%)	(59.2%)	(56.9%)
Total	100%	100%	100%
	(100%)	(100%)	(100%)

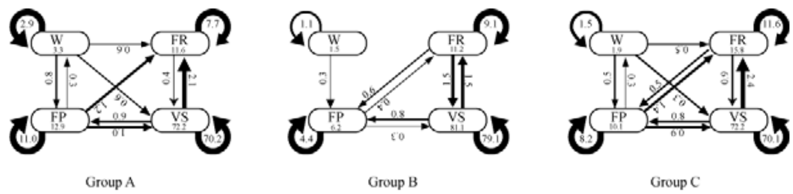
Table 3 : Relative composition e of building use types of the whole region

Use type	Group A	Group B	Group C
Void Space	72.2%	81.1%	72.1%
Housing	19.7%	8.9%	15.0%
	(71.0%)	(46.9%)	(53.9%)
Commercial Building	4.0%	3.8%	6.4%
	(14.3%)	(20.2%)	(23.0%)
Public Building	2.1%	2.4%	2.9%
	(7.6%)	(12.7%)	(10.3%)
Agricultural or Industrial Building`	2.0%	3.8%	3.6%
	(7.1%)	(20.2%)	(12.8%)
Total	100%	100%	100%
	(100%)	(100%)	(100%)

5.2 Comparison of state transition

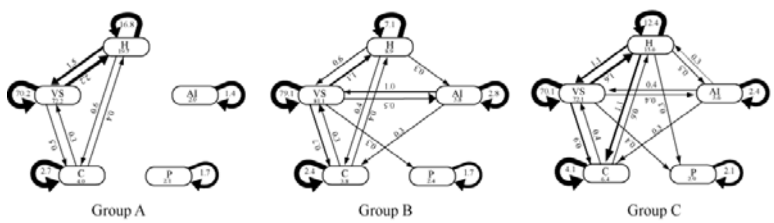
The state transition diagram was created from the stochastic transition matrix of each group.

Figure 9 is the state transition diagrams of building structures, and Figure 10 is the state transition diagrams of building use types. In these diagrams, the numbers under the name of items indicate the relative compositions of each item in 1996, and the value on arrows and the thickness of arrows express the relative space of the area, in which the corresponding transition is generated. If the index is 0.2% or less, those are not shown in these two figures. The following characteristics can be drawn out from figures.



W : Wooden Building
FP : Fire-prevention Building
FR : Fire resistant Building
VS : Void Space

Figure 9 : State transition diagram of building structure



H : Housing
C : Commercial Building
P : Public Building
AI : Agricultural or Industrial Building
VS : Void Space

Figure 10 : State transition diagram of building use type

5.2.1 Group A

Since the rate of the transition to a fire prevention building and a fire-resistant building from a wooden building and the transition to a fire-resistant building from a fire prevention building are large, the fire prevention performance of this group is considered to be improved. In addition, there are also many transitions to a fire prevention building and a fire-resistant building from void spaces (Figure 9, left). On the other hand, although the transitions to other use types from industrial, agricultural and public are few, but the transition among housing, commercial building and void space has occurred often. Especially, the big transition has occurred interactively between housing and void space, and there seems to be a lot of transition of use types as housings being rebuilt to new housings via void spaces (Figure 10, left).

Therefore, Groups A is characterized to be that urbanization has progressed, and the transition of public, agricultural and industrial buildings is independent from other use types.

5.2.2 Group B

The transition to fire prevention buildings from wooden buildings, fire-resistant buildings and void spaces has exceeded the extent of the transition to the reverse directions, and consequently it is considered that fire prevention buildings increases relatively (Figure 9 center). On the other hand, agricultural and industrial buildings seems to change to void spaces, and void spaces seems to change to housing, commercial and public buildings (Figure 10 center).

Therefore, the areas of Group B are under urbanization. In addition, because of the decrease of agricultural and industrial buildings and void spaces, and the increase of housing and commercial fire prevention buildings, the relative composition of fire-resistant buildings seems to decrease relatively.

5.2.3 Group C

Like Group A, there are many transitions to fire prevention and fire-resistant buildings from wooden buildings, and there are also many transitions to fire-resistant buildings from fire prevention buildings. Therefore Group C is considered to have similar trend to Group A on this point (Figure 9 right).

However, since there are also many transitions between industrial, agricultural and public buildings, Group C is similar to Group B on this point (Figure 10 right).

Therefore, Group C can be characterized as a district with the interim specificity of Group A and Group B.

As a whole, when there is a little transition between industrial or agricultural buildings and housing or commercial buildings, the index α

tends to become better. On the other hand, when there are a lot of those transitions, the index α tends to become worse.

It is important to say that results obtained in this study are for the data sets of 1991 and 1996. In order to avoid the effect of peculiar characteristics of these data sets if there is any, similar analysis should be applied for other data sets.

6. CONCLUSION

The following facts turned out from the above interpretations.

1. As a whole, the relative composition of a fire-resistant building will increase eventually in Tokyo.
2. The relative composition of the fire prevention building will decrease, especially in the northeast and the northwest parts of Tokyo. The relative composition of the fire-resistant building will increase, and many fire-resistant buildings will be seen even in the distant district from the center district at the converged state.
3. The city area where the index α is low can be expected to expand to the limb parts in the future. It is considered that the index α will become worse in the future in a littoral district or the center district of Tokyo.
4. When there is a little transition between industrial or agricultural buildings and housing or commercial buildings, the index α tends to become better. On the other hand, when there are a lot of those transitions, the index α tend to become worse.

These results obtained for the data sets of 1991 and 1996 suggest that fire prevention performance may become worse in the future in the area where urbanization is newly advancing.

Moreover, in order to use these results for damage mitigation of a big earthquake disaster, it is necessary to examine how to change state transition matrix by controllable ways.

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