Decision Making on Safety Diagnosis and Renewal of Old Wooden Houses - Model Analysis

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ABSTRACT

In the Hanshin-Awaji earthquake in 1995, many old wooden houses collapsed, and as a result a number of people died. This disaster was a reminder that there still exists a significant volume of old houses which were constructed based on the old building code. It is becoming critical to check the safety of these old houses and improve their quality. In order to help household owners to obtain a status and information on quality of their houses, some local governments in Japan have empirically introduced a safety diagnosis scheme.

In this study, a decision making model on safety diagnosis and renewal of old houses is constructed. Their effects of structural deterioration are also taken into account. Owner’s age and history of a house have an influence on the decision to invest in renewal. When the result of diagnosis does not affect owner’s decision on renewal, an owner does not have an incentive to obtain information by safety diagnosis.

Even if it is rational for an owner not to take safety diagnosis, the collapse of their houses may affect utilities of other people. For example, it may increase the risk of fire, which can spread to other houses. In such a case, government's subsidizing policies may improve social welfare by encouraging owners to take safety diagnosis. In this study the effect of subsidizing policies is also analyzed.

1. INTRODUCTION

In the Great Hanshin-Awaji earthquake in 1995, more than 60,000 houses collapsed, and more than 7,000 houses were burned [1]. This disaster reminded Japanese people of the existence of such a high percentage of old houses which have already decayed over time and become so vulnerable. Even if the new building code is established, such houses based on an old building code remain in a city. It is becoming critical to improve the quality of them.

Responsibility of maintaining safety of houses may rest with owners, in principle. However, even if it is rational for an owner not to implement house renewal, the collapse of their houses may degrade utilities of other people. For example, collapse of houses could cause a fire that might spread to other areas in the city. When the damaged area is a historical district, the collapse of houses may affect the cultural landscape and amenity of the whole city. For this reason, it is often necessary that the government encourages owners to implement house renewal. With a view to conducting a policy analysis, a mathematical model of owner's decision on house renewal is constructed in this paper.

In many cases, an owner does not know exactly about the extent of decay of their houses. The evaluation of safety requires the knowledge of expertise. In this paper, safety check by experts is called "seismic safety diagnosis." Owner's decision on taking seismic safety diagnosis is incorporated into the model. The effectiveness of government's intervention in owners' decision through subsidies is also discussed.

2. TEMPORAL TRANSITION OF QUALITY OF A HOUSE

2.1 Temporal Transition of Amenity and Safety

We assume a representative (average) owner of an old house. In our model, quality of a house consists of two attributes. One is amenity, and the other is safety. Amenity is the attribute that determines owner's utility in usual periods. On the other hand, the conditions of house after an earthquake depend on safety.

Time degrades both amenity and safety. In our model, while amenity is a deterministic variable with respect to time, safety is a probabilistic one. Although an owner can obtain perfect information on amenity, they cannot obtain perfect information on safety before he or she takes seismic safety diagnosis (**Table 1**).

Let t be the time. Decisions on house renewal and seismic safety diagnosis are made at t = 0. Remaining lifetime of an owner and history of houses at t = 0 are defined as T and h (T,h>0), respectively. That is, the house was built at t = -h, and owner's utility is calculated from t = 0 to t = T (See **Figure 1**).

It is assumed that amenity decays exponentially with time (See **Figure 2**). $a(t)$, the amenity at t, is defined as follows.

$$a(t) = e^{-\alpha(h+t)} \tag{1}$$

Here α represents the parameter of decay of amenity.

Table 1 Properties of Houses in the Model

Amenity	**Safety**
Deterministic	Probabilistic
Perfect Information	Imperfect Information

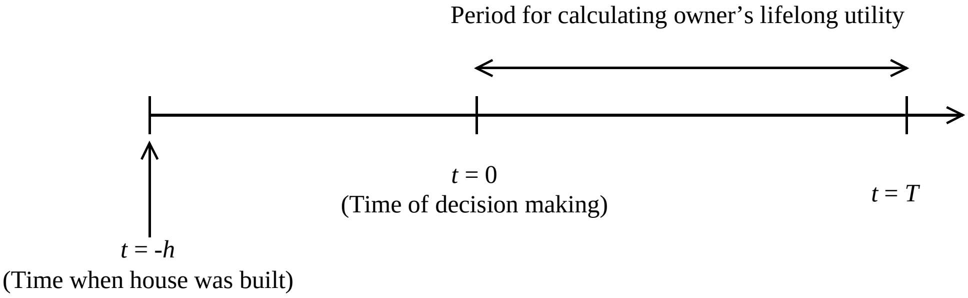

Figure 1 History *h* and remaining lifetime *T*

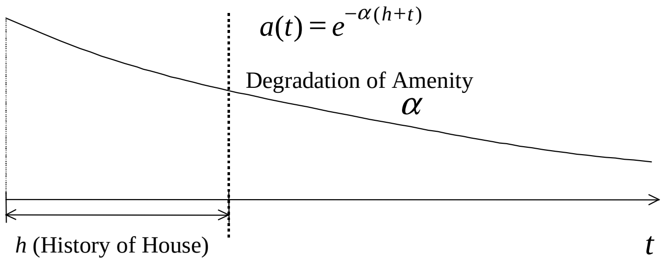

Figure 2 Decay of Amenity

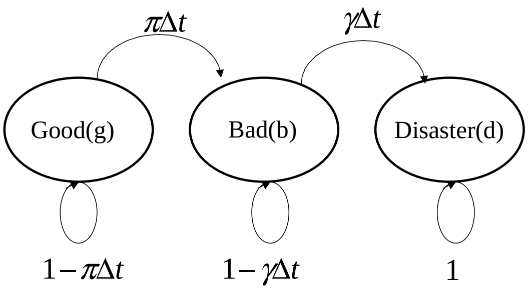

Figure 3 Transition between States

For the sake of simplicity, safety consists of only two states, "good" and "bad." A "good" house makes a transition to "bad" over time. This transition is irreversible. An owner cannot know which state the house is in, given a particular point in time. The difference in the state of safety does not affect amenity in a non-disaster (normal) period. However, "bad" house will definitely collapse when an earthquake occurs. It is also assumed that no "good" house will collapse in an earthquake. The probabilities that the states of houses at *t* are "good (*g*)", "bad (*b*)," and "disaster (collapse)(*d*)" are defined as $P_g(t), P_b(t), P_d(t)$, respectively. Transition probabilities from *g* to *b* and from *b* to *d* are π and γ. **Figure 3** shows the transition between these states.

Following differential equations can be formulated.

$$\frac{dP_g(t)}{dt} = -\pi P_g(t) \qquad \frac{dP_b(t)}{dt} = \pi P_g(t) - \gamma P_b(t) \qquad \frac{dP_d(t)}{dt} = \gamma P_b(t) \tag{2}$$

In order to solve these differential equations, initial conditions need to be specified. The probabilities of those states in which time *s* has passed since the time when the state was found to be "good" are defined as

Table 2 t_i, $a(0)$, $P_g(0)$, and $P_b(0)$ in case house renewal or seismic safety diagnosis is implemented at *t* = 0

	t_i	$a(0)$	$P_g(0)$	$P_b(0)$

House Renewal	0	1	1	0
Seismic safety diagnosis (Result: "good")	0	$e^{-\alpha h}$	1	0
Seismic safety diagnosis (Result: "bad")	0	$e^{-\alpha h}$	0	1

$P_{gg}(s), P_{gb}(s)$, and $P_{gd}(s)$. These probabilities can be obtained from **Equation** (2) as follows.

$$P_{gg}(s) = e^{-\pi s}, \quad P_{gb}(s) = \frac{\pi(e^{-\gamma s} - e^{-\pi s})}{\pi - \gamma}, \quad P_{gd}(s) = 1 - \frac{\pi e^{-\gamma s} - \gamma e^{-\pi s}}{\pi - \gamma} \tag{3}$$

The probabilities of those states in which time *s* has passed since the time when the state was found to be "bad," $P_{bg}(s), P_{bb}(s)$, and $P_{bd}(s)$ are written as

$$P_{bg}(s) = 0, \quad P_{bb}(s) = e^{-\gamma s}, \quad P_{bd}(s) = 1 - e^{-\gamma s} \quad . \tag{4}$$

Let the probability that the state at $t = -h$ is "good." be P_g^0. An owner knows that the house is not collapsed at $t = 0$. In other words, the state of the house at $t = 0$ is not *d*, but *g* or *b*. This additional information determines the probabilities of states at $t = 0$ as follows.

$$\tilde{P}_g = P_g^0 e^{-\pi h}, \quad \tilde{P}_b = 1 - P_g^0 e^{-\pi h} \tag{5}$$

The prior probabilities of states at *t* ($t > 0$), $P_g(t), P_b(t), P_d(t)$ can be derived as follows.

$$P_g(t) = \tilde{P}_g P_{gg}(t) \qquad P_b(t) = \tilde{P}_g P_{gb}(t) + \tilde{P}_b P_{bb}(t) \qquad P_d(t) = \tilde{P}_g P_{gd}(t) + \tilde{P}_b P_{bd}(t) \tag{6}$$

2.2 Transitions in Case

The following are the definitions of "House Renewal" and "Seismic safety diagnosis" in our model.

Definition 1: House Renewal
The action taken by an owner that recovers both amenity and safety at the time when the house was built.

Definition 2: Seismic safety diagnosis
The action provided by an expert that specifies the state of safety of owner's houses at the time of diagnosis.

The last time when an owner obtains certain information on safety, is defined as t_i. **Table 2** shows t_i, $a(0)$, and $P_g(0), P_b(0)$ in case house renewal or seismic safety diagnosis is implemented at $t = 0$. When house renewal is implemented at $t = 0$, $a(t)$ and $P_g(t)$, $P_b(t)$ and $P_d(t)$ after renewal $(t \geq 0)$ are formulated as follows:

$$a(t) = e^{-\alpha t} \tag{7}$$

$$P_g(t) = P_{gg}(t) = e^{-\pi t}, \qquad P_b(t) = P_{gb}(t) = \frac{\pi(e^{-\gamma t} - e^{-\pi t})}{\pi - \gamma}, \qquad P_d(t) = P_{gd}(t) = 1 - \frac{\pi e^{-\gamma t} - \gamma e^{-\pi t}}{\pi - \gamma} \tag{8}$$

When an owner takes seismic safety diagnosis at $t = 0$, $P_g(t)$, $P_b(t)$ and $P_d(t)$ $(t \geq 0)$ depend on the result of diagnosis. If the result of diagnosis is "good," $a(t)$, $P_g(t)$, $P_b(t)$ and $P_d(t)$ are determined by **Equations** (1), and (8), respectively. If the result of diagnosis is "bad", we obtain

$$P_g(t) = P_{bg}(t) = 0 \qquad P_b(t) = P_{bb}(t) = e^{-\gamma t} \qquad P_d(t) = P_{bd}(t) = 1 - e^{-\gamma t} \qquad (t \geq 0) \tag{9}$$

$a(t)$ is given by **Equation** (1).

3□DECISION MAKING ON HOUSE RENEWAL AND SAFETY DIAGNOSIS

3.1 Owner's Utility

Owner's utility at t depends on the quality of the house and income. Owner's quasi-linear utility function $u(t)$ is defined in case that the house does not collapse at t.

$$u(t) = y(t) + v(t) \tag{10}$$

where $y(t)$ is owner's income at t. $v(t)$ is determined depending on amenity $q(t)$. $v(t)$ is called "partial utility" in this paper. The present value of $v(t)$ at $t = 0$ is shown as follows:

$$v(t) = B_0 a(t) e^{-\beta t} = B_0 e^{-\alpha(h+t)-\beta t} \tag{11}$$

β is a time discount rate. Before taking seismic safety diagnosis, the present value of owner's lifelong partial utility is shown as follows:

$$B_u(T,h) = \int_{t=0}^{T} \{P_g(t) + P_b(t)\} v(t) dt \tag{12}$$

3.2 Decision Making Model on House Renewal

Decision making on house renewal and seismic safety diagnosis is represented by the decision tree as shown in **Figure 4**. First, an owner decides whether it takes seismic safety diagnosis or not. After seismic safety diagnosis, the current state on safety is reported to an owner. This is a chance node that does not depend on owner's decision. Finally, an owner decides whether it implements house renewal or not. It can also select house renewal even if he or she does not take seismic safety diagnosis. By using Equations (1)-(12), the present value of owner's lifelong expected partial utility is calculated as follows.

In case house renewal is implemented,

$$\begin{aligned} B_r(T) &= \int_{t=0}^{T} \{P_g(t) + P_b(t)\} v(t) dt \\ &= \int_{t=0}^{T} B_0 \{e^{-\pi t} + \frac{\pi(e^{-\gamma t} - e^{-\pi t})}{\pi - \gamma}\} e^{-\alpha t - \beta t} dt \end{aligned} \tag{13}$$

When house renewal is implemented, the lifelong expected partial utility always takes the same value (equation (13)).

In case the result of diagnosis is "good" and house renewal is not implemented,

$$\begin{aligned} B_g(T,h) &= \int_{t=0}^{T} \{P_g(t) + P_b(t)\} v(t) dt \\ &= \int_{t=0}^{T} B_0 \{e^{-\pi t} + \frac{\pi(e^{-\gamma t} - e^{-\pi t})}{\pi - \gamma}\} e^{-\alpha(t+h) - \beta t} dt \end{aligned} \tag{14}$$

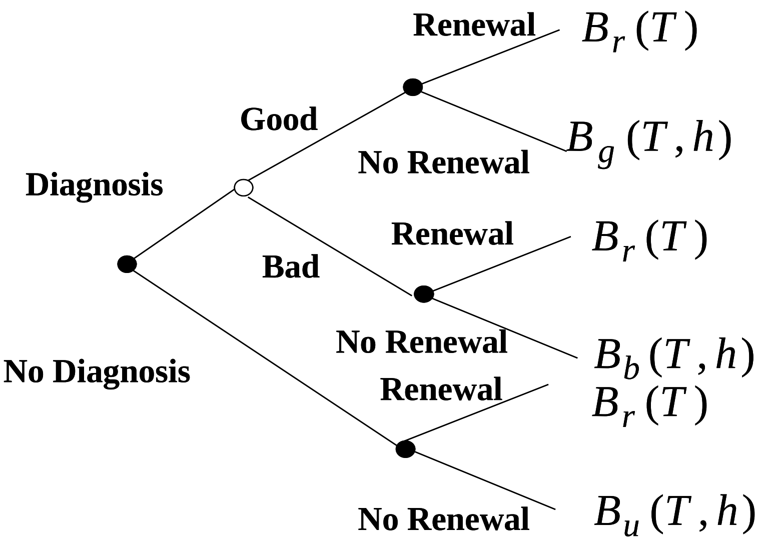

Figure 4 Decision Making Model on House Renewal and Seismic Safety Diagnosis

In case the result of diagnosis is "bad" and house renewal is not implemented,

$$\begin{aligned} B_b(T,h) &= \int_{t=0}^{T} \{P_g(t)+P_b(t)\} v(t)dt \\ &= \int_{t=0}^{T} B_0 e^{-\gamma t} e^{-\alpha(t+h)-\beta t} dt \end{aligned} \tag{15}$$

In case neither seismic safety diagnosis nor house renewal is implemented,

$$\begin{aligned} B_u(T,h) &= \int_{t=0}^{T} [\tilde{P}_g\{P_{gg}(t)+P_{gb}(t)\} + \tilde{P}_b P_{bb}(t)] v(t)dt \\ &= \int_{t=0}^{T} B_0\{P_g^0 e^{-\pi(t+h)} + P_g^0 e^{-\pi h} \frac{\pi(e^{-\gamma t}-e^{-\pi t})}{\pi-\gamma} + (1-P_g^0 e^{-\pi h}) e^{-\gamma t}\} e^{-\alpha(t+h)-\beta t} dt \end{aligned} \tag{16}$$

The following inequalities are always satisfied.

$$B_b(T,h) \le B_u(T,h) \le B_g(T,h) \le B_r(T) \tag{17}$$

Let the costs of house renewal and seismic safety diagnosis be C_R and C_I. The net value of house renewal is the difference between the increment of the lifelong expected partial utility by renewal and the cost of renewal.

In case seismic safety diagnosis is not implemented,

$$f_1(T,h) = B_r(T) - B_u(T,h) - C_R \tag{18}$$

In case the result of diagnosis is "good",

$$f_2(T,h) = B_r(T) - B_g(T,h) - C_R \tag{19}$$

In case the result of diagnosis is "bad",

$$f_3(T,h) = B_r(T) - B_b(T,h) - C_R \tag{20}$$

where $f_1(T,h)$, $f_2(T,h)$, and $f_3(T,h)$ are monotone increasing functions of T and h.

When the net value of house renewal is positive, an owner selects house renewal. From **Equation** (17) we obtain $f_2(T,h) \le f_1(T,h) \le f_3(T,h)$. Thus the curves $f_1(T,h)=0$, $f_2(T,h)=0$, and $f_3(T,h)=0$ can be illustrated such as **Figure 5**. The conditions for house renewal in the four cases on seismic safety diagnosis are also shown in **Figure 5**. An owner makes one of following decisions, depending on the region:

a) $f_2(T,h) > 0,\ f_1(T,h) > 0,\ f_3(T,h) > 0$:
An owner always implements house renewal. Owner's decision does not depend on the result of seismic safety diagnosis.

b) $f_2(T,h) \le 0,\ f_1(T,h) > 0,\ f_3(T,h) > 0$:
When the result of seismic safety diagnosis is "bad," an owner implements house renewal. When the result is "good," he or she does not implement house renewal. If seismic safety diagnosis is not implemented, an owner chooses house renewal.

c) $f_2(T,h) \le 0,\ f_1(T,h) \le 0,\ f_3(T,h) > 0$:
When the result of seismic safety diagnosis is "bad," an owner implements house renewal. When the result is "good," it does not implement house renewal. If seismic safety diagnosis is not implemented, an owner does not choose renewal.

d) $f_2(T,h) \le 0,\ f_1(T,h) \le 0,\ f_3(T,h) \le 0$:
An owner does not implement house renewal. Owner's decision does not depend on the result of seismic safety diagnosis.

From the above discussions, owner's decisions in our model can be summarized as follows:
□Older owner's incentive for house renewal becomes weak.
□Owners of older houses have strong incentives for house renewal.

The existence of safety diagnosis affects owner's decision making on house renewal.

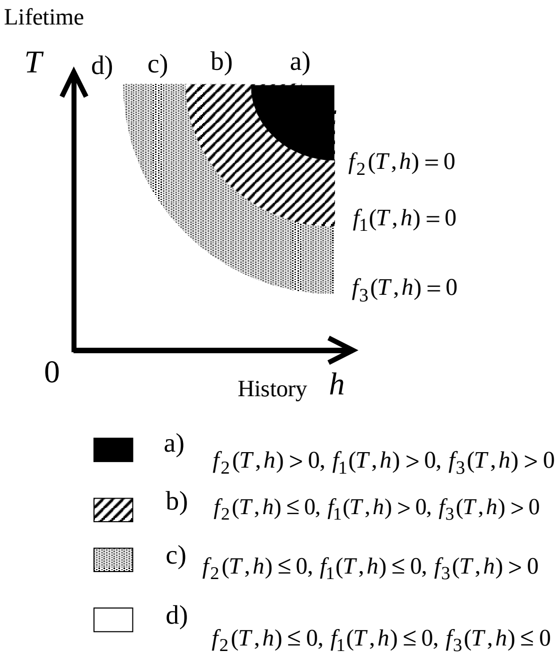

Figure 5□Relationship between Lifetime *T*, History *h* and Decision on Renewal

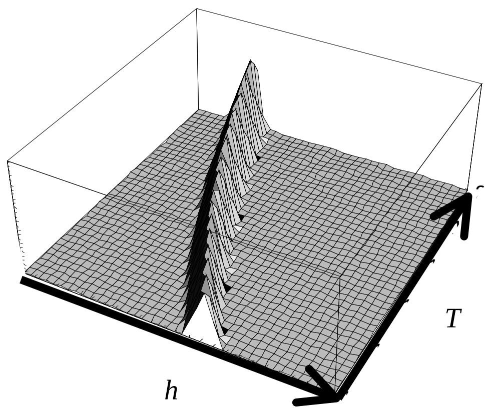

Figure 6 Net Value of Safety Diagnosis (Example)

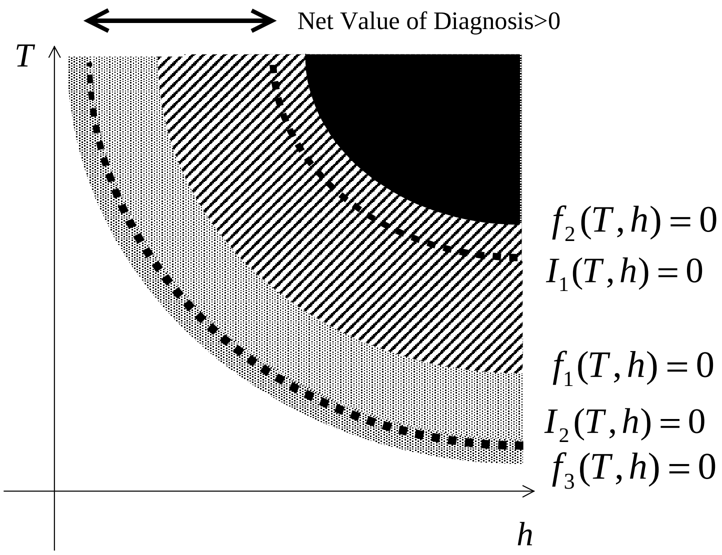

Figure 7 Directions of Decreasing Net Value of Diagnosis

3.3 Decision Making Model on Seismic Safety Diagnosis

Seismic safety diagnosis should be implemented when the result of diagnosis affects decision-making on house renewal. In other words, an owner takes seismic safety diagnosis in case that $f_2(T,h) \le 0, f_1(T,h) > 0, f_3(T,h) > 0$ (b) in **Figure 5**) or $f_2(T,h) \le 0, f_1(T,h) > 0, f_3(T,h) > 0$ (c) in **Figure 5**). The value of seismic safety diagnosis is determined by the value of information obtained from diagnosis. The net value of seismic safety diagnosis is calculated as follows.

b) $f_2(T,h) \le 0, f_1(T,h) > 0, f_3(T,h) > 0$

$$I_1(T,h) = [\tilde{P}_g B_g(T,h) + \tilde{P}_b\{B_r(T) - C_R\}] - \{B_r(T) - C_R\} - C_I \tag{21}$$

c) $f_2(T,h) \le 0, f_1(T,h) > 0, f_3(T,h) > 0$

$$I_2(T,h) = [\tilde{P}_g B_g(T,h) + \tilde{P}_b\{B_r(T) - C_R\}] - B_u(T,h) - C_I \tag{22}$$

Proposition 1 regarding $I_1(T,h)$ and $I_2(T,h)$ can be shown as follows.

Proposition 1

$f_2(T,h) \le 0, f_1(T,h) > 0, f_3(T,h) > 0$:

$$\frac{\partial I_1}{\partial T} < 0, \frac{\partial I_1}{\partial h} < 0 \tag{23}$$

$f_2(T,h) \le 0, f_1(T,h) > 0, f_3(T,h) > 0$:

$$\frac{\partial I_2}{\partial T} > 0, \frac{\partial I_2}{\partial h} > 0 \tag{24}$$

Figure 6 shows the example of the positive net value of seismic safety diagnosis. The net value of seismic safety diagnosis is positive in the region shown by the arrow in **Figure 7**. The net value remains 0 along the broken lines ($I_1(T,h) = 0$ and $I_2(T,h) = 0$). We obtain following conclusions from the analysis.

- When T and h are large enough or small enough, the net value of seismic safety diagnosis becomes negative. If the possibility that renewal improves the lifelong expected utility is high, an owner implements house renewal without diagnosis. Similarly, if the possibility of improving the lifelong expected utility is low, an owner does not take diagnosis, and nor does implement renewal. In both cases, the value of information is too small for an owner to pay the cost of diagnosis.
- The net value of seismic safety diagnosis takes the highest value along the curve $f_1(T,h) = 0$. When $f_1(T,h) = 0$, the lifelong expected partial utilities of house renewal and no renewal are found to be indifferent. Consequently, if an owner does not take diagnosis, two alternatives on renewal (renewal and no renewal) are equally preferable. By taking seismic safety diagnosis, it becomes possible for the owner to compare them and choose the alternative whose lifelong expected utility is higher.

3.4 Value of Information for Choosing Alternative

In the analysis in **3.2** and **3.3**, it is assumed that an owner can choose an appropriate alternative for renewal without any advises. In the real case, an owner does not necessarily know how their houses should be renewed, therefore the information for choosing an alternative of house renewal is also provided in safety diagnosis.

Suppose that there are two alternatives for house renewal. Let the probabilities of transition from g to b be π_1 and π_2 . The parameter of decay of amenity (α) is same in both alternatives. It is assumed that $\pi_1 < \pi_2$. That means that the probability that the state is “Bad” at the house renewed in one alternative is always higher than that at the house renewed in another alternative. An owner knows that the probabilities of transition are different in two alternatives, but an owner does not know which alternative can make a house safer. After safety diagnosis, an owner can obtain the information on the probabilities of transition in each alternative correctly.

Owner's lifelong expected partial utility in case of house renewal without safety diagnosis is defied as $B_r^u(T)$. $B_r^u(T)$ is always smaller than lifelong expected partial utility in case of house renewal after safety diagnosis $B_r(T)$, because an owner may choose a more dangerous alternative without safety diagnosis.

Comparing with the case that $B_r^u(T) = B_r(T)$, decreases and $I_1(T,h)$ increases ($f_2(T,h), f_3(T,h)$, and $I_2(T,h)$ are not affected.) As the result, the curve $I_1(T,h) = 0$ moves to upper right in **Figure 7**. That means that more owners may take safety diagnosis in case owners do not know the appropriate alternative for house renewal.

4. DECISION MAKING WITH SUBSIDIZING POLICIES

In this section, the effects of subsidizing policies are discussed. **Figure 8** shows decision making model on house renewal with subsidizing policies of government. First, the government chooses a subsidizing policy. The government can also take a noninterference policy without subsidizing. The government informs an owner of its decision. Consequently, an owner has perfect information on whether he or she can receive subsidy in each case.

Based on this information, an owner makes decision to maximize the lifelong expected utility. This model can be interpreted as a noncooperative game in an extensive form. That means that a subgame perfect equilibrium can be derived by using backward induction. In this section, the following three policies are discussed.

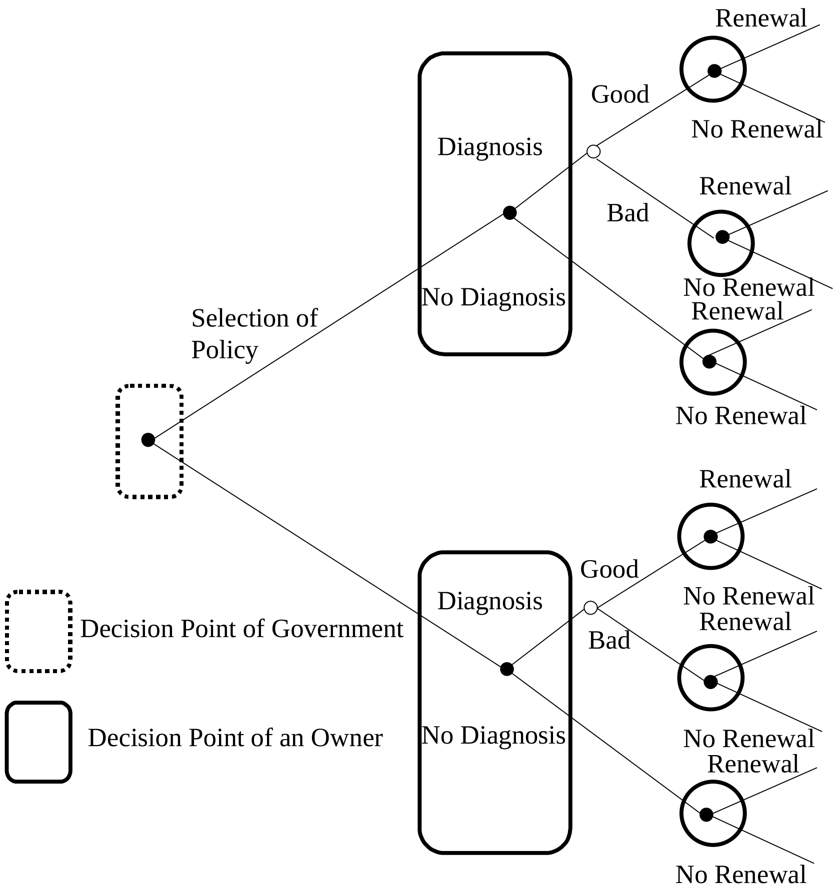

Figure 8 Decision Making Model on House Renewal with Government's Policy

1. Subsidies for Seismic safety diagnosis
 The amount of subsidy is S_I .
2. Subsidies for Renewal of Houses Judged to be "Bad" in Seismic safety diagnosis
 The amount of subsidy is S_R .

$f_1(T,h)$, $f_2(T,h)$, $f_3(T,h)$, $I_1(T,h)$, and $I_2(T,h)$ are changed by subsidizing policies as follows.

1. Subsidies for seismic safety diagnosis

$$f_1(T,h) = B_r(T) - B_u(T,h) - C_R \quad (25)$$

$$f_2(T,h) = B_r(T) - B_g(T,h) - C_R \quad (26)$$

$$f_3(T,h) = B_r(T) - B_b(T,h) - C_R \quad (27)$$

$$I_1(T,h) = \{\tilde{P}_g B_g(T,h) + \tilde{P}_b \{B_r(T) - C_R)\} - \{B_r(T) - C_R\} - C_I + S_I \quad (28)$$

$$I_2(T,h) = \{\tilde{P}_g B_g(T,h) + \tilde{P}_b \{B_r(T) - C_R)\} - B_u(T,h) - C_I + S_I \quad (29)$$

2. Subsidies for renewal of house judged to be "bad"

$$f_1(T,h) = B_r(T) - B_u(T,h) - C_R \tag{30}$$
$$f_2(T,h) = B_r(T) - B_g(T,h) - C_R \tag{31}$$
$$f_3(T,h) = B_r(T) - B_b(T,h) - C_R + S_R \tag{32}$$
$$I_1(T,h) = \tilde{P}_g B_g(T,h) + \tilde{P}_b\{B_r(T) - C_R\} - \{B_r(T) - C_R\} - C_I + \tilde{P}_b S_R \tag{33}$$
$$I_2(T,h) = \tilde{P}_g B_g(T,h) + \tilde{P}_b\{B_r(T) - C_R\} - B_u(T,h) - C_I + \tilde{P}_b S_R \tag{34}$$

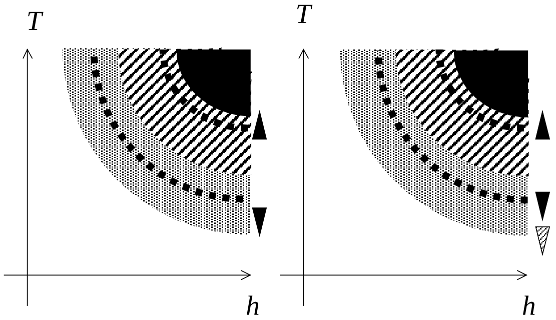

Figure 9 Effects of Government's Policies to Owners' Decision: Subsidies for Diagnosis(Left), Subsidies for Renewal of Houses Judged to be "Bad" in Seismic safety diagnosis (Right)

Equations (25)-(34) indicate the alternation of boundaries on owner's decision, as shown in **Figure 9**. The results are shown as follows:

- When the government subsidizes seismic safety diagnosis, the curve $I_1(T,h) = 0$ moves to upper-right, and the curve $I_2(T,h) = 0$ moves to lower left. That results in that the region where an owner takes seismic safety diagnosis becomes large. Subsidizing policy 1 is effective in promoting a seismic safety diagnosis and implementing renewal for a "bad" house.
- When the government subsidizes renewal of the house which is judged to be "bad" in seismic safety diagnosis, the increase of the net value of seismic safety diagnosis is $P_b(0) \times S_R$. In consequence the curve $I_1(T,h) = 0$ moves to upper-right, and the curves $f_3(T,h) = 0$ and $I_2(T,h) = 0$ move to lower left. That means that subsidizing policy 2 has the same effect as subsidizing policy 1 in promoting seismic safety diagnosis.

The above analysis shows that subsidizing seismic safety diagnosis is effective in promoting old house renewal. Even if government subsidizes house renewal itself, the information obtained from seismic safety diagnosis can be used to make the policy more efficient.

However, subsidizing policies may not necessarily make an owner take seismic safety diagnosis. As shown in **Figure 8**, the owner whose value of information is small will not have incentive to take seismic safety diagnosis.

6. CONCLUSION

In this paper, a mathematical model on seismic safety diagnosis and house renewal was constructed to analyze owner's decision making process. The model can explain the relationship between owner's choices and temporal properties of an owner (remaining lifetime) and the house (history). The effectiveness of subsidizing policies by the government has also been discussed, and the model analysis has shown that the policies incorporating seismic safety diagnosis can improve the efficiency of subsidizing, given certain conditions met.

For further study, the following points needs to be incorporated into the model.

- The efficiency of subsidizing policies from the viewpoint of the whole city
- The external effect of old houses in normal period
- The external effect of collapse of old houses in earthquake
- The difference of risk perceptions between owners and the government

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