Community Restoration/Relocation Planning Model for Safety, Convenience and Sustainability

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ABSTRACT

In several communities affected by the Tsunami of the Great East Japan Earthquake on March 11, 2011, fierce discussion had been done over the restoration/relocation plan of the community. They faced to difficult trade-off between safety from next disaster and convenience for daily life. Moreover, the down trend of population and economic activities there required the need of sustainability check for the relocation plan. Certain number of users must be provided for the reopened facility and local transportation service. Unfortunately, the Japanese Government did not wait for the complete consensus for community restoration/relocation plan based on rational or scientific consideration over the possible land-use and facility location possibilities; for many cases, relocation to high elevated land was decided as political propaganda without enough reasoning.

We propose an optimal model of sustainable land-use, which can be used in community restoration/relocation planning both in post-disaster restoration plan and disaster prevention relocation plan in possible disaster prone area. The model controls, residential and activity facility locations, relocation of inhabitants, activity related people's trip pattern, as well as public transportation line in a destructed region. It minimizes several social cost composed by construction, trips, facility operation, transportation service operation, and psychological relocation cost of the people. Using linear objective function weighting those partial objectives, the proposed model can be formulated as a mixed integer linear programming model, which can be numerically solved by general solver programs.

We discuss the reasonability of the restoration plan in Shizugawa Town Case, where, residential use is banned in ex-downtown near the coast line, and three high elevated areas will be used for relocation of facilities as well as residential houses. The model shows the conditions that such high-land development and totally relocation policy becomes reasonable.

Keywords:
compact city, land-use planning, scale of facilities, scale of public transportation

1. Introduction

In several tsunami-stricken areas affected by the Great East Japan Earthquake, a new land-use plan is being devised to move inhabitants from areas designated as hazardous to a higher elevation. However, as for move to higher elevations, the safety can be ensured, but psychological repulse can occur because of an attachment to former residence. In addition, an inconvenient of commuting is also the big problem because there are many resident working for fisheries who had the damage of the tsunami. Therefore, only higher elevation move is not a good plan, and it is necessary to make a new land-use plan while considering such a trade-off relation between safety and convenience. Moreover, due to the decreasing population trend, the sustainability of public services (e.g., public transportation, hospital, school, factory, etc.) must be accounted for in the plan.

Okumura et al. (2012) suggested a mixed integer linear programming model for sustainable land-use planning. This model considered the minimum-scale user of public facilities and transportation for compactness and sustainability.

In this study, we adopted this model, and applied it to both hypothetical and real area settings where are needed new land-use planning, to analyze the locations of residence and activity facilities, assignment of the inhabitants. We can suggest which zone we should develop in consideration of number of inhabitant and activity facilities. Furthermore, the effects of the scale restrictions on land use are presented.

2. Formulation of the land-use planning model

Okumura et al. (2012) proposed a sustainable land-use planning model for disaster-affected areas. This section describes the mixed integer linear programming model. Disaster stricken and hazardous areas can be considered as former residences. New residences correspond to the proposed hill sites; activity facilities included work places, a fishery facility, a shopping center, hospital, school, and so on. In this model, we explicitly considered the sustainable condition as minimum number of users to maintain facilities and public transportation.

The parameters and variables of the model are defined as follows:

Definition parameters

k : Zone of former residence
i : Zone of new residence
j : Zone in which facilities are placed
a : Activity in facilities
b_i : Maintenance cost of infrastructure in Zone *i*
h_i : Unit construction cost of house per person in Zone *i*
e_j^a : Unit construction cost of Facility *a* in Zone *j*(per facility)
d_i : Disaster risk per capita of nighttime in Zone *i*
d_j^a : Disaster risk per capita of Facility *a* in Zone *j*
c_{ki} : Moving cost from Zone *k* to Zone *i*
t_{ij} : Distance between Zone *i* and Zone *j*
u_0^a : Fixed maintenance cost of Facility *a*
v_0 : Fixed maintenance cost of public transportation
u^a : Variable running cost per capita of Facility *a*
v_p : Variable running cost per capita of public transportation
l^a : Frequency of trip generation for Activity *a*
P_k : Population of Zone *k*
M^a : Capacity of Facility *a*
N^a : Minimum number of users to sustain Facility *a*
R : Capacity of public transportation
Q : Minimum number of users to sustain public transportation
f : Unit size of the area of a house
g^a : Unit size of the area of Facility *a*
F_i : Size of the area that can be developed in Zone *i*
τ^a : Critical walkable distance to Facility *a*

Instrumental variables

$S_i = \{0,1\}$: Dummy variable to express whether Zone *i* is developed as a location for residences or facilities
$X_i^k \geq 0$: Number of people to move from Zone *k* to Zone *i*
$Y_j^a = \{0,1\}$: Dummy variable to express whether Facility *a* is placed in Zone *j*
$Z_{ij}^a \geq 0$: Number of people to use Facility *a* of Zone *j* in the population of Zone *i*
$W_{ij} = \{0,1\}$: Dummy variable to express whether public transportation exists between Zone *i* and Zone *j*

$r_{ij}^a = \{0,1\}$: Dummy variable to express whether Facility a exists within the critical walkable distance between Zone i and Zone j

For the minimization objective function, six partial objective functions are considered. The infrastructure maintenance cost and construction costs of houses and facilities are expressed in Function E. Functions C, D and T represent the total moving cost, disaster risk, and the total distance from residence area to facilities, respectively. Here, disaster risk consists of nighttime and daytime risk. Sustainment costs for transportation and facilities are expressed in Function V and U, respectively. These partial objective functions are shown in Equations (1)–(6). The minimization objective function of this model is represented Equation (7), which is a weighted linear function of partial objectives.

Partial objective functions

$$E = \sum_i \left(b_i S_i + h_i \sum_k X_i^k \right) + \sum_j \sum_a \left(e_j^a Y_j^a \right) \tag{1}$$

$$C = \sum_j \sum_a \left(c_{ki} X_i^k \right) \tag{2}$$

$$D = \sum_i d_i \sum_k X_i^k + \sum_j \sum_a \left(d_j^a \sum_i Z_{ij}^a \right) \tag{3}$$

$$T = \sum_a \sum_i \sum_j \left(t_{ij} Z_{ij}^a \right) \tag{4}$$

$$V = \sum_i \sum_j \left(v_0 t_{ij} W_{ij} + v_p t_{ij} \sum_a Z_{ij}^a \right) \tag{5}$$

$$U = \sum_a \sum_j \left(u_0^a Y_j^a + u^a \sum_i Z_{ij}^a \right) \tag{6}$$

Objective function (weighted linear function of partial objectives)

$$\min_{S,X,Y,ZW} \beta_e E + \beta_c C + \beta_d D + \beta_t T + \beta_v V + \beta_u U \tag{7}$$

where, $\beta_e, \beta_c, \beta_d, \beta_t, \beta_v, \beta_u$ are weights of each partial objective function.
The Followings are constraint conditions:

Constraints

$$\sum_i X_i^k = P_k \quad \forall i \in I, \forall k \in K \tag{8}$$

$$l^a \sum_k X_i^k = \sum_j Z_{ij}^a \quad \forall i \in I, \forall a \in A \tag{9}$$

$$r_{ij}^a = \begin{cases} 1, & if\ t_{ij} \le \tau^a \\ 0, & if\ t_{ij} > \tau^a \end{cases} \quad \forall i \in I, \forall a \in A \tag{10}$$

$$Z_{ij}^a \le M^a \left(W_{ij} + r_{ij}^a \right) \quad \forall i \in I, \forall a \in A \tag{11}$$

$$\sum_i Z_{ij}^a \le M^a Y_j^a \quad \forall j \in I, \forall a \in A \tag{12}$$

$$\sum_i Z_{ij}^a \ge N^a Y_j^a \quad \forall j \in I, \forall a \in A \tag{13}$$

$$\sum_a Z_{ij}^a \le R W_{ij} + M r_{ij} \quad \forall i, j \in I \tag{14}$$

$$\sum_a Z_{ij}^a \ge Q W_{ij} \quad \forall i, j \in I \tag{15}$$

$$f \sum_k X_i^k + \sum_a g^a Y_i^a \le F_i S_i \quad \forall i \in I \tag{16}$$

Each constraint condition represents as follows:
· Conservation between the inhabitants and facility users in the network (as Equations (8) and (9))
· Accessibility constraint to usable facilities by public transportation and/or on foot (as Equations (10) and (11))
· Necessary conditions to maintain facilities (as Equations (12) and (13))
· Necessary conditions to maintain public transportation (as Equations (14) and (15))
· Limitations of the developed area size (as Equation (16)).

3. Hypothetical data setting

The formulated model is applied to a hypothetical area to verify the validity of the model in this section. Data were set putatively, and the optimum solution was computed. The results were analyzed the effects on minimum user numbers of public facilities and transportation to the optimal land use.

3.1. Hypothetical research area

The hypothetical area is shown in Figure 1, and is divided into three zones ($i = 1,2,3$): seaside, level ground, and elevation. The seaside zone (Zone 1) and level ground zone (Zone 2) both had 50 occupants ($P_1 = 50, P_2 = 50$). We assumed that the disaster occurred, and that the elevation zone (Zone 3) was under consideration for new residency. Use of the seaside zone (Zone 1) required an additional cost for protection against natural disasters. Preparation and maintenance infrastructure costs were required for elevation zone (Zone 3) development. The level ground zone (Zone 2) had minimal maintenance costs for its infrastructure. Only two activities in the facilities ($a = 1,2$) were considered for each zone ($j = 1,2,3$). The maintenance costs of the infrastructure (b_i), and construction costs for house (h_i) and facilities (e_j^a) are shown in Table 1. The construction cost of the higher area was greater than those of lower areas.

The usable space in each zone (F_i) is also expressed in Table 1. It is possible that all inhabitants live together in Zone 1, but impossible in Zone 2 and 3. Earthquakes and Tsunamis were considered as the disaster risks in this study; thus, Zone 1 would be the highest risk area and Zone 3 is the lowest risk area. The risk of disasters occurring during nighttime or daytime hours (d_i,d_j^a) is shown in Table 2.

The distances between areas (t_{ij}) and moving costs (c_{ki}) from former to post residence are represented Table 3 and 4, respectively. Moving costs take into account the psychological repulse, as well as the physical distance. All parameters for the two activities are assumed to be identical (Table 5). The parameters for public transportation are shown in Table 6.

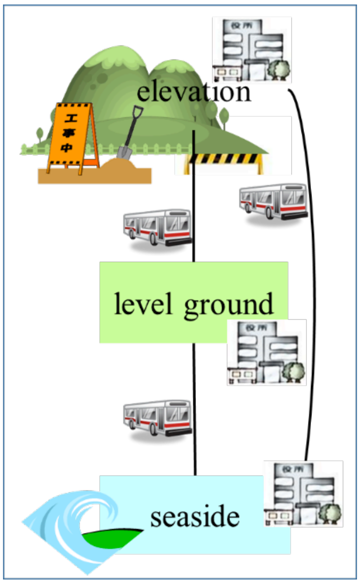

Figure 1. Hypothetical areas

Table 1. Maintenances and construction costs, and usable space

	b_i	h_i	e_j^1	e_j^2	F_i
Zone 1	1500	20	200	200	200
Zone 2	500	30	300	300	100
Zone 3	6000	60	600	600	100

Table 2. Risk of disaster

	d_i	d_j^1	d_j^2
Zone 1	10	10	10
Zone 2	5	5	5
Zone 3	1	1	1

Table 3. Distance between Zone *i* and Zone *j* (t_{ij})

i \ j	1	2	3
1	10	100	150
2	100	10	100
3	150	100	10

Table 4. Moving cost from Zone *k* to Zone *i* (c_{ki})

k \ i	1	2	3
1	1	2	3
2	2	1	2

Table 5. Parameters for activities

	l^a	M^a	N^a	g^a	u_0^a	u^a	τ^a
$a = 1$	0.5	100	0 / 30	10	1	1	30
$a = 2$	0.5	100	0 / 30	10	1	1	30

Table 6. Parameters for public transportation

	v_0	v_p	R	Q
Bus	10	1	100	20

3.2. Analysis results of hypothetical sets

The optimum solution was computed according to change in the partial objective function weights, $\boldsymbol{\beta}$. The sum of the six weight components equals $1(= \beta_e + \beta_c + \beta_d + \beta_t + \beta_v + \beta_u)$. When one weight, β changes its value to another value between 0 and 1 (at a 0.001 interval), then the other weight components change by the same value, $(1 - \beta)/5$.Minimum number of users to sustain facility (N^a) was considered as constraint in Equation (13). The cases when minimum number of user is reflected ($N^a = 30$) and not ($N^a = 0$) are discussed in this section.

The results of developed zone and inhabitant number according to change in the weight for disaster risk (β_d) are shown in Figure 2 and 3 (when $N^a = 0$). According to Figure 2, when disaster risk was smaller than 0.17 ($0 \leq \beta_d < 0.17$), seaside zone (Zone 1) and level ground zone (Zone2) were developed on the condition that the number of user to maintain facilities were zero ($N^a = 0$). Disaster risk is increasing up, consequently, elevation place (Zone 3) is developed instead of seaside and level ground. Zone 1 and Zone 2 both had 50 occupants when disaster risk was low ($0 \leq \beta_d < 0.06$) in Figure 3. When disaster risk was between 0.06 and 0.17 ($0.06 \leq \beta_d < 0.17$), 80 occupants lived in Zone 2 and 20 occupants in Zone 1. When disaster risk is greater than 0.17 ($0.17 \leq \beta_d \leq 1$), nobody lived in Zone 1. And Zone 3 had started to be developed the same as Figure 2. 80 occupants lived in Zone 3 and 20 occupants lived in Zone 2.

By contrast, when minimum user number to sustain facility was conditioned ($N^a = 30$), the results were changed such as Figure 4 and 5. Only Zone 1 was developed when disaster risk was low ($0 \leq \beta_d < 0.2$) to keep up the minimum user, N^a. When disaster risk was high ($0.2 \leq \beta_d \leq 1$), Zone 2 and Zone 3 had started to be developed. 20 and 80 occupants lived in Zone 2 and Zone 3, respectively.

According the results, we could know that the developed area has a deep relationship with the weight components and minimum number of user to sustain facilities. And number of assigned inhabitant is also changed according to the weights and sustainable number.
The computed results showed reasonable tendency, thus, we can say that the validity of the model was verified.

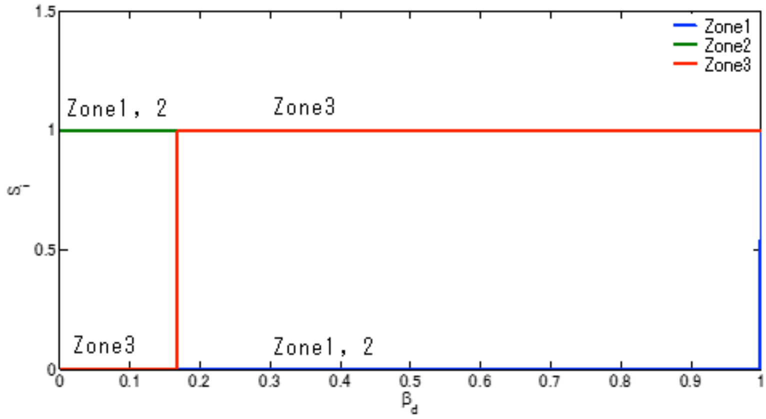

Figure 2. Developed zone according to change in the weight for disaster risk (β_d)
(when $N^a = 0$)

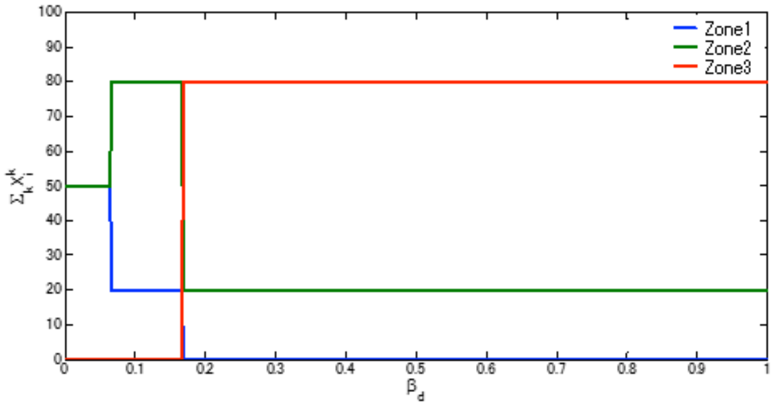

Figure 3. Number of inhabitant according to change in the weight for disaster risk (β_d)
(when $N^a = 0$)

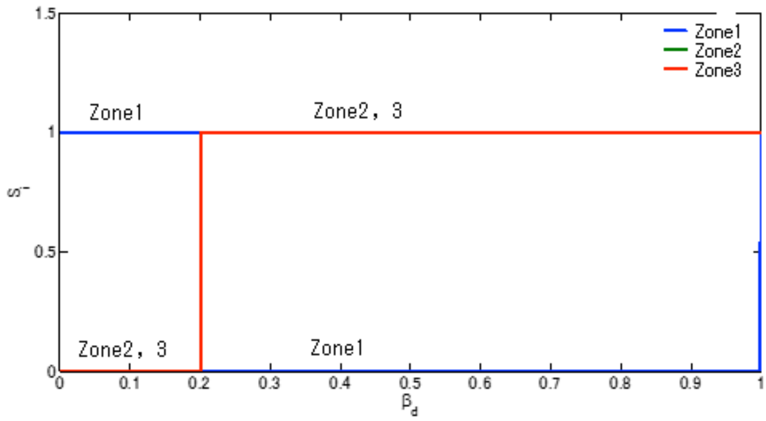

Figure 4. Developed zone according to change in the weight for disaster risk (β_d)
(when $N^a = 30$)

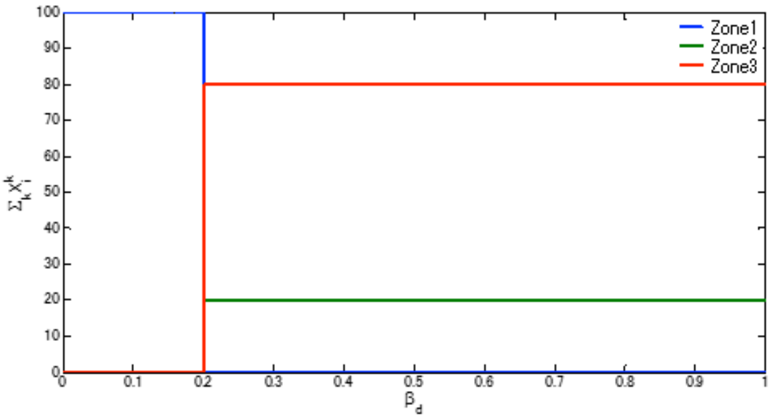

Figure 5. Number of inhabitant according to change in the weight for disaster risk (β_d)
(when $N^a = 30$)

4. Real data setting

In this section, the model was applied to real area, Shizugawa in Minamisanriku. Set data were referred to disaster prevention and move promotion plan of Shizugawa in 2012. In this section, we will discuss the practicality of the model.

4.1. Real research area

The research area is Shizugawa area in Minamisanriku town where was hit by the Great East Japan Earthquake. There is a river in the middle of the town (shown in Figure 6) which flooded about one kilometers radius at the Earthquake and Tsunami. A town hall was flooded up to the 4th floor and Shizugawa hospital was flooded up to the 5th floor. The population before the Earthquake was 8,406 people.

Disaster prevention and move promotion plan of Shizugawa was drafted September 2012. According to the plan, four zones are considered as reconstructed areas. Coastal area (Zone 1) is the former suffered residence, and elevation areas (Zone 2, 3 and 4) are new suggested residence such as Figure 6.

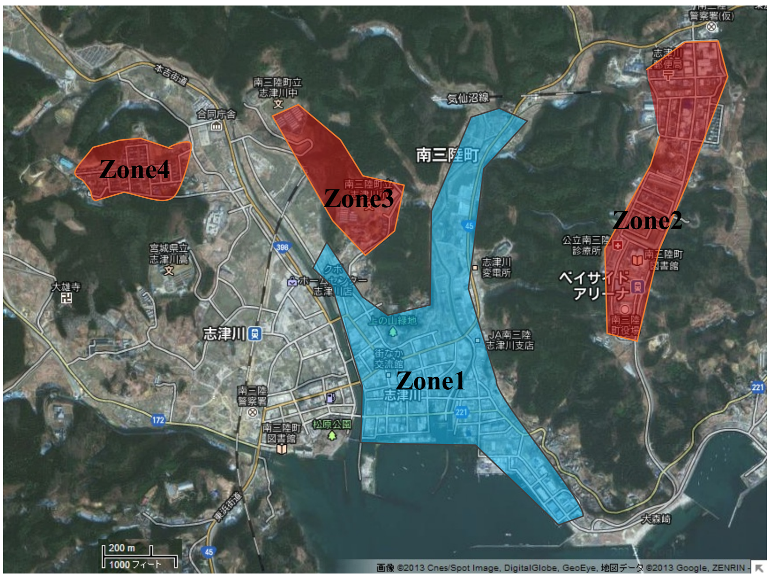

Figure 6. Research area (Shizugawa in Minamisanriku)

Four activities ($a = 1,2,3 and 4$) were assumed in this section; using a town hall, seeing a doctor regularly, commuting for work, and going to school. Maintenances costs of infrastructure (b_i), construction costs for house (h_i), facilities (e_j^a), and the usable space in each zone (F_i) are expressed in Table 7. Because of building an embankment, raising of road and so on, b_i is most expensive in Zone 1. And because marine products processing factory must be in Zone 1, e_1^3 is also expensive.

The risk of disaster occurring during nighttime or daytime hours (d_i, d_j^a) is represented in Table 8. The distances between zones (t_{ij}) and moving costs (c_{ki}) from former to post residence are represented in Table 9 and 10, respectively. Parameters for the four activities and parameters for public transportation are shown in Table 11 and Table 12. Minimum number of users to sustain facility (N_j^a) is represented in Table 13.

Moreover, population of Zone 1 is assumed 1,231 and unit size of the area of a house is assumed 330 ($P_1 = 1231, f = 330$).

Table 7. Maintenances and construction costs, and usable space

	b_i	h_i	e_j^1	e_j^2	e_j^3	e_j^4	F_i
Zone1	5.4×10^9	7.2×10^6	3.0×10^7	2.8×10^9	3.7×10^8	3.0×10^9	6.0×10^5
Zone2	2.4×10^9	7.2×10^6	3.0×10^7	2.8×10^9	1.8×10^8	4.6×10^9	2.4×10^5
Zone3	2.6×10^9	7.2×10^6	3.0×10^7	2.8×10^9	1.8×10^8	1.6×10^9	1.6×10^5
Zone4	2.4×10^9	7.2×10^6	3.0×10^7	2.8×10^9	1.8×10^8	4.6×10^9	0.8×10^5

Table 8. Risk of disaster

	d_i	d_j^1	d_j^2	d_j^3	d_j^4
Zone1	7.2×10^6	3.2×10^6	3.6×10^6	3.6×10^6	3.6×10^6
Zone2	1.0	0.5	0.5	0.5	0.5
Zone3	1.0	0.5	0.5	0.5	0.5
Zone4	1.0	0.5	0.5	0.5	0.5

Table 9. Distance between Zone i and Zone j (t_{ij})

i \ j	1	2	3	4
1	0.3	3.2	1.7	2
2	3.2	0.3	1.5	4.5
3	1.7	1.5	0.3	3
4	2	4.5	3	0.3

Table 10. Moving cost from Zone k to Zone i (c_{ki})

k \ i	1	2	3	4
1	0.3	3.2	1.7	2

Table 11. Parameters for activities

	l^a	M^a	g^a	u_0^a	u^a	τ^a
$a = 1$	0.14	1231	2100	3.00×10^8	0	0.50
$a = 2$	0.22	1231	5580	8.62×10^8	0.02	0.50
$a = 3$	0.54	1231	4400	1.67×10^6	0	0.50
$a = 4$	0.10	1231	15600	2.05×10^7	7.00×10^4	0.50

Table 12. Parameters for public transportation

	v_0	v_p	R	Q
Bus	9.7×10^5	2.0×10^{-5}	1231	81

Table 13. Minimum number of users to sustain facility (N_j^a)

j \ a	1	2	3	4
1	100	100	200	100
2	100	100	10	100
3	100	100	10	100
4	100	100	10	100

4.2. Analysis results of real sets

Development of zone and assignment of inhabitant and facility location according to change in weight components of partial objective function are discussed using the calculated results.

The relationship between number of inhabitant and weight for disaster risk is shown in Figure 7. According to this figure, Zone 1 is not developed as residence for any value of the disaster risk weight. This is attributed to extremely high risk (d_i, d_j^a) in Table 8. Inhabitants were distributed to elevation areas (Zone 2, 3 and 4) depending on size of the areas.

Figure 8 is expressed change of inhabitant number according to the weight for construction cost. The tendency of Figure 8 is similar to Figure 7 when the weight for construction cost is less than 0.94 ($0 \leq \beta_e < 0.94$) but it is different when the weight is more than 0.94 ($0.94 \leq \beta_e \leq 1$).
Figure 9 represents whether work place exists in Zone *j* or not ($Y_j^3 = \{0,1\}$) according to change of the weight for construction cost. When the weight is less than 0.87 ($0 \leq \beta_e < 0.87$), work place exists in Zone 2, 3 and 4. But work place is located in Zone 3 and 4 when the weight is over 0.87 ($0.87 \leq \beta_e < 0.94$). When the weight is more than 0.94 ($0.94 \leq \beta_e < 1$), work place is located in only Zone 3. And because there is no work place in Zone 4, the number of inhabitant decreases at the same time such as Figure 8.

Moreover, when only the weight for construction cost is considered ($\beta_e = 1, and\ \beta_c = \beta_d = \beta_t = \beta_v = \beta_u = 0$) in Figure 8 and 9, only Zone 1 is developed and all activity facilities are distributed also in Zone 1 because of minimize construction cost. This tendency is the same when the weight for moving cost (β_c), transportation cost (β_t) and running cost of transportation (β_v) are 1 respectively (Figure 10, 11 and 12). On the other hand, according to Figure 13, because minimum number of users to sustain work place in Zone 1 (N_1^3) is extremely high, work place facility is not built in Zone 1 although there is large space when the weight for running cost of facility is considered.

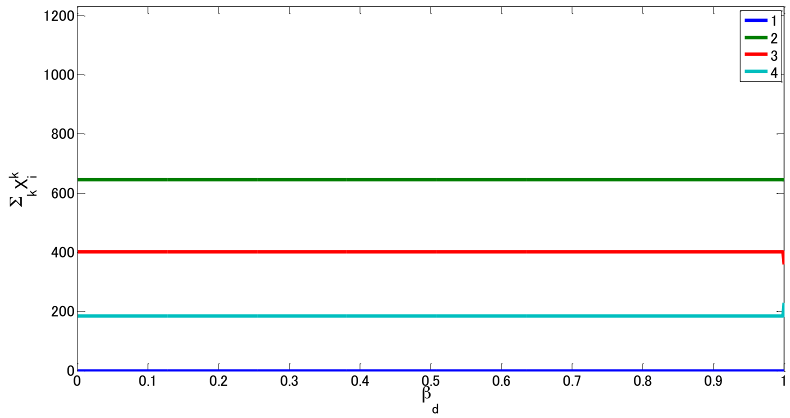

Figure 7. Change of inhabitant number according to the weight for disaster risk (β_d)

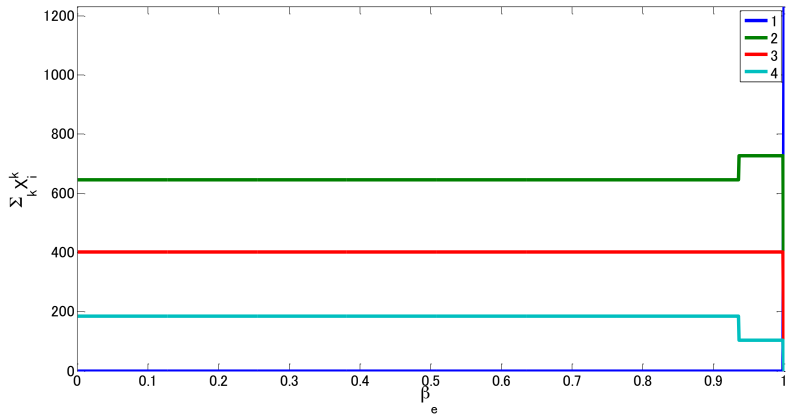

Figure 8. Change of inhabitant number according to the weight for construction cost (β_e)

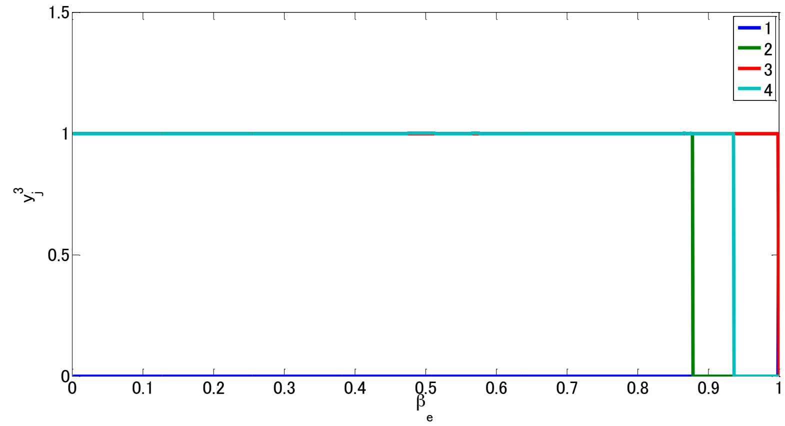

Figure 9. Change of work place existence (Y_j^3) according to the weight for construction cost (β_e)

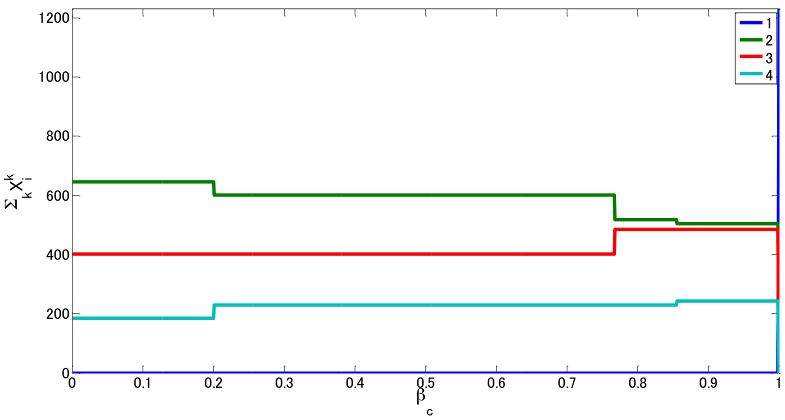

Figure 10. Change of inhabitant number according to the weight for moving cost (β_c)

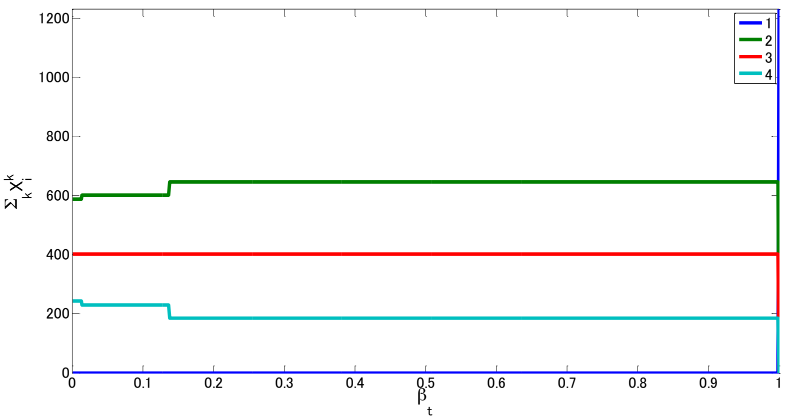

Figure 11. Change of inhabitant number according to the weight for transportation cost (β_t)

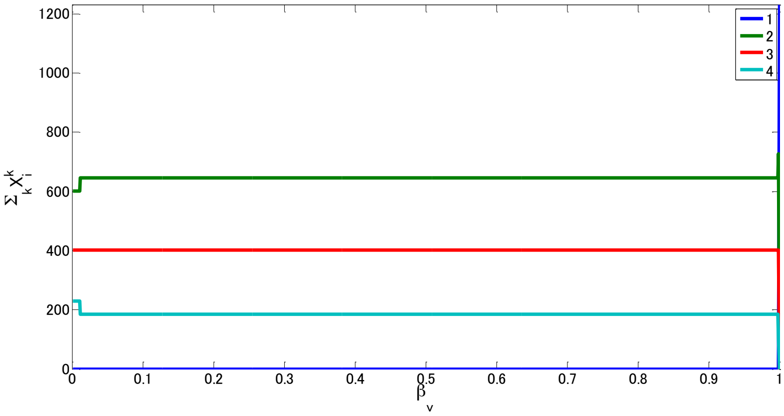

Figure 12. Change of inhabitant number according to the weight for running cost of transportation (β_v)

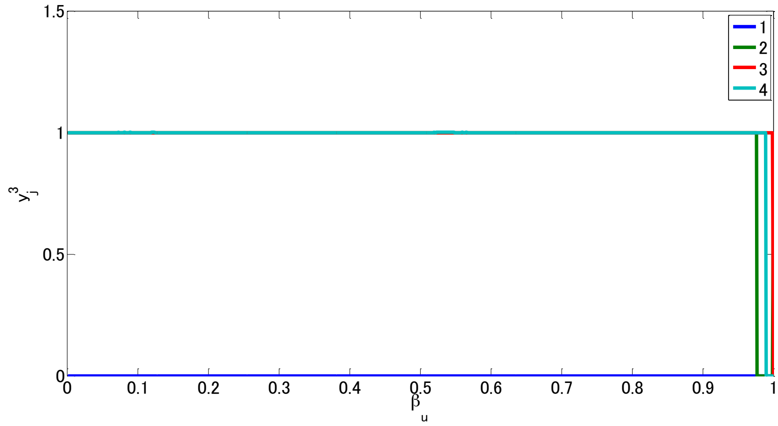

Figure 13. Change of work place existence (Y_j^3) according to the weight for running cost of facility (β_u)

According to the weight components, developed zone and its size were changed. And we could know which facility must exist in each Zone. It means this model can be applied to any area with adjusting the priority of weights to situation.

5. Conclusions

The proposed model was applied to hypothetical zone settings to verify the validity of the model and to real zone settings to confirm the practicality of the model. And we analyzed the effects of minimum user numbers of public facilities and transportation to optimal land use. Six weight components of partial objective function: maintenance and construction cost of houses and facilities, total moving cost, disaster risk, total distance from residence area to facilities and sustainment cost for transportation and facilities are considered in this study, and the followings were clarified:

· Land use (zone for residence or facility) and assigned inhabitant number are changed according to the weights of partial objective function.
· Land use and assigned inhabitant number are changed according to minimum-scale user to maintain public services.
· The six weight components of partial objective function affect it each other.

Using this model, we can suggest which zone we should develop in consideration of number of inhabitant and activity facilities. Moreover, it was possible to set minimum-scale user of public facilities and transportation to keep a compactness and sustainability in this model.
According to the results, it is expected that this model can be applied to any area with adjusting the priority of weights to situation.

Reference:

1. Okumura, M., Okubo, K., Kim, J., Tirtom, H., 2012. Optimal model of sustainable land-use for disaster restoration planning. Presented at the 26th Applied Regional Science Conference, in Aomori Public University (in Japanese).
2. Minamisanriku Town reconstruction maintenance plan: Disaster prevention and move promotion plan of Shizugawa, 2012 (in Japanese)
3. Ministry of Land, Infrastructure, Transport and Tourism: Suffering situation investigation, http://www.mlit.go.jp/common/000214811.pdf (in Japanese)