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TRANSPORTATION-LAND USE MODEL FOR EVALUATION OF TRAFFIC FACILITIES

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JAPAN

1. Introduction

It is essential to forecast land use changes for assessment of the effectiveness of large-scale investment in traffic facilities because land use change is a fundamental determinant of traffic generation, environmental changes, increases in capital gains from land, etc.

Studies on land use have been developed in various fields such as geography, economics and engineering. As shown in Fig. 1, von Thünen's agricultural land rent theory[1] based on land productivity and Weber's theory of industry location preference[2] have been developed into more general location theories of urban land uses. On the other hand, computer models of land use have also been developed using operational and quantitative research methods. Many land use models have been developed since Lowry's model(1964).[3] However, most of these models do not describe well the real process of deciding on land uses in densely populated regions such as urban areas in Japan. More detailed models, which should be able to show more precisely actual land use distributions, are required to assess the effectiveness of investments in traffic facilities.

The land use model which is proposed in this paper was developed in order to forecast future land use patterns in a suburban area of Tokyo where land use patterns have greatly changed in recent years.

2. Land price function

Land use depends upon the utility to the land user. The utility of each plot of land is in general represented by the rent of the plot. In forecasting land use, one might wish ideally to be able to isolate the various major factors which determine rent. However, because it is not easy to collect sufficiently reliable rent data for each plot of land, our analysis makes use of land price data, which are compiled every year and are announced to the public. Using such data, we shall first attempt to construct a land price function for each land use pattern.

Such functions are constructed for each of the following land uses: residential areas, central commercial areas, and industrial areas. Examples will be shown for the following two land use patterns.

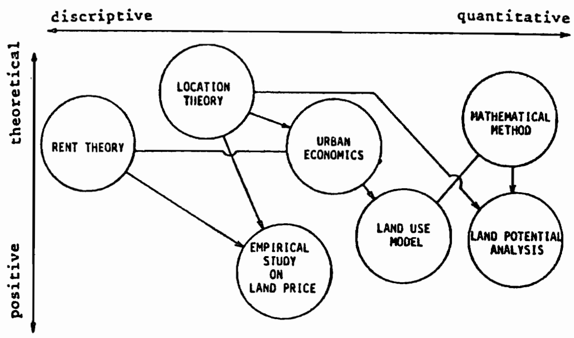

Fig. 1 Genealogy of land use research

a) Residential areas

It is assumed that the land price is dependent upon such factors as ease of commuting, natural environment, availability of public utilities, plot size , and "maturity" of a given area.

These conditions are represented by such indicators as shown in Table 1. Using land price data for a number of sample plots and the corresponding indicators, application of quantification theory I*) gives the land price function shown in Table 1. It shows that ease of commuting is the most dominant factor, thus corroborating already existing theories and studies. At the same time, the table shows that availability of public utilities also has a fairly large bearing on land price.

b) Central commercial areas

Land price function is induced, in ways similar to the case of residential areas, from data at sample points as shown in Table 2. In order to estimate "potentiality of purchase" by inhabitants of surrounding areas, two indicators are used in the analysis, with the assumption the distances to commercial areas are measured radially in the case of walking or travel by vehicles other than trains, and are measured in terms of travel time for areas along nearby rail lines.

Table 2 shows that two indicators, (1) the proportion of existing commercial area within a grid, and (2) distance to the nearest railway station have the greatest effect upon land price. Land prices, and therefore land use values, of commercial areas decrease with distance from the nearest station at steeper rates than in the case of residential areas.

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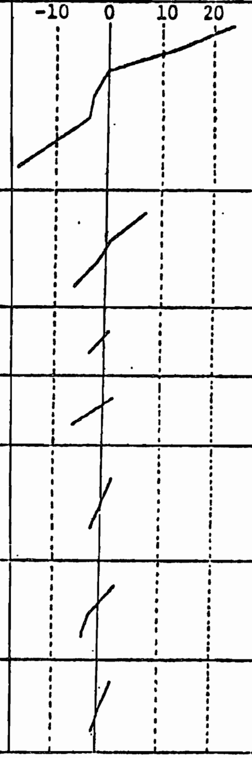
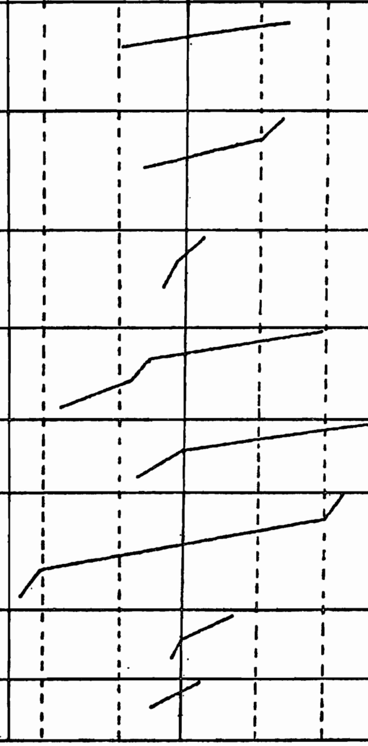
*) Quantification theory I is a kind of dummy variable method of multiregression analysis, which can be applied in cases where independent variables stand for non-quantifiable categories and also in cases where independent variables have a non-liear relationship with the dependent variable.

Table 1 Estimated scores for land price function in residential area

Factor	Indicator	Category number	Category	Number of samples	Category score (yen/m²)	Difference (thousand yen/m²) -10 0 10 20	Range (yen/m²)	Partial correlation coefficient
Commuting condition	Average travel time from nearest railway station to place of work	1	0 - 40 minutes	13	66,065		39,965	0.677
		2	40 - 50	72	56,376			
		3	50 - 60	79	41,452			
		4	60 - 70	110	40,711			
		5	70 - 80	77	38,297			
		6	80 - 90	32	31,687			
		7	90 - 120	50	26,100			
	Distance to nearest railway station	1	0 - 500 meters	47	11,777		11,777	0.314
		2	500 - 1200	157	5,896			
		3	1200 - 2200	148	3,629			
		4	farther than 2200	81	0			
Natural Environment	Terrain	1	Alluvial plain	249	2,323		2,323	0.120
		2	Hills	184	0			
Availability of public utilities	Level of gas and sewerage availability	1	One or both utilities	240	8,852		8,852	0.394
		2	None	190	0			
	Land-readiustment area	1	More than 25% within 1 km² grid	170	3,329		3,329	0.168
		2	Less than 25% within 1 km² grid	263	0			
Maturity of area	Percentage of DID area in 1960 within 1 km² grid	1	75 - 100 %	122	5,431		5,431	0.217
		2	25 - 75	94	3,260			
		3	0 - 25	217	0			
Comfortability	Size of house	1	More than 280 m²	87	5,251		5,251	0.197
		2	180 - 280	200	2,550			
		3	Less than 180	146	0			

(multiple correlation coefficient = 0.816)

Table 2 Estimated score for land price function in central commercial areas

Factor	Indicator		Category number	Category	Number of samples	Category score (yen/m²)	Difference (thousand yen/m²) -100 -50 0 50 100	Range (yen/m²)	Partial correlation coefficient
Potentiality of purchase of goods	Purchase by local inhabitants	Σ(population in i surrounding grid i/distance (i-j))	1	more than 250,000	42	355,983		123,464	0.261
			2	less than 250,000 (persons/km)	91	232,520			
		Σ(population in i grid i along rail lines/ travel time (i-j)	1	more than 300,000	19	101,650		101,650	0.223
			2	less than 300,000	16	82,589			
			3	(persons/minute)	98	0			
	Purchase by commuters	Σ(number of employees in work place w/travel time(w-j))	1	more than 18,000	16	27,480		27,480	0.039
			2	3,500 - 18,000	84	5,430			
			3	less than 3,500 (persons/minute)	33	0			
Degree of commercial agglomeration	Percentage of existing commercial area within 1 km² grid		1	more than 10%	32	201,203		201,203	0.297
			2	4 - 10	51	78,922			
			3	1 - 4	29	52,269			
			4	0 - 1	21	0			
	Number of big stores within 1 km² grid		1	more than 3	21	168,475		168,475	0.268
			2	1 or 2	30	35,800			
			3	0	82	0			
Transportation convenience of site	Distance to nearest railway station		1	0 - 100 meters	25	0		238,831	0.474
			2	100 - 200	27	-15,690			
			3	200 - 500	41	-139,149			
			4	500 - 750	22	-225,215			
			5	farther than 750	18	-238,831			
	Frequency of trains to and from nearest station		1	0 - 3 minutes	13	0		49,455	0.064
			2	3 - 20	77	-41,232			
			3	more than 20	43	-49,455			
Maturity of area	Percentage of DID area in 1960 within 1 km² grid		1	50 - 100%	83	0		41,437	0.092
			2	0 - 50	50	-41,437			

(multi-correlation coefficient = 0.702)

3. A model to forecast land use

(1) Classification of land uses

Land uses are classified into the following four types.

(a) priority location type ----- large-scale basic industries, universities, large-scale parks and greens, government offices, public utilities, military facilities
(b) competitive location type ----- single-family houses, apartment houses, commercial centers, light industries
(c) subsequent location type ----- neighbourhood stores, schools and libraries, streets, neighbourhood parks
(d) passive location type ----- agricultural fields, forests

The location and amount of type (a) use is determined a priori on the basis of the existing development plan of a given area. Type (b) use locates competitively as in the case of housing or stores in densely inhabited districts. Type (c) are land uses which are determined in proportion to the amount of land alloted to type (a) and (b) use. In contrast to these urban land uses, type (d) is largely agricultural land use which is considered to play a role in the supply of new sites for urban land uses because of its low return.

(2) Model framework for land use changes

For type (c) use, "land user" is defined here as a composite of land use (κ) and various attributes (ω) of the user.

In the case of housing, for example, a land user is defined as a commuter whose land use (κ) is housing and whose working place (ω) is central Tokyo. As for industry, the "land user" is assigned attributes which are classified according to type of product, namely, primal products, intermediate products, or final products.

The major assumption in von Thünen's theory of spatial equilibrium, namely, that the user who locates at a given site will be that user which can obtain the largest utility, is even now generally being applied to location theory in regard to housing and other urban land uses.
Fig. 2 gives a generalized illustration of von Thünen's concept which shows land use distribution as a function of distance from the city center in a uni-centered city according to the bid price level of each land user in proportion to the utility to be expected from each site.

But in reality, the kind of land use at a given site is determined not only by utility but also by land price. Alonso[5] applied the utility maximization

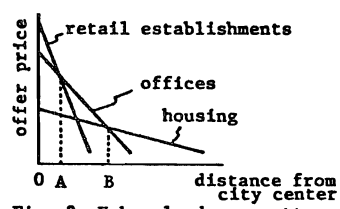


Fig. 2 Urban land use pattern [4] and offer price (Goodall, 1972)

theorem to housing location with an assumed restriction of budgets for land purchases according to income level. Even this concept does not consider the relative intensity of demand on the part of each prospective land user among various sites.

In the model proposed in this paper, the "locational surplus" is defined as the difference between locational utility to a land user to be expected from a site and the land price. The following two assumptions are made in regard to location.

(a) A prospective land user will wish to locate on a site with maximum locational surplus to him
(b) Under competition among land users for a given site, the land user who has the maximum locational surplus locates there.

On the other hand, land price for each land use is measured quantitatively according to land quality by quantification theory I, and locational utility is derived therefrom.

Then it is possible to express the site location preference of each land user as well as the location process under conditions of competition from other would-be land users. The concept of the process of land use changes is summarized as follows with reference to Fig. 3. The main players in the process are land users of competitive location type.

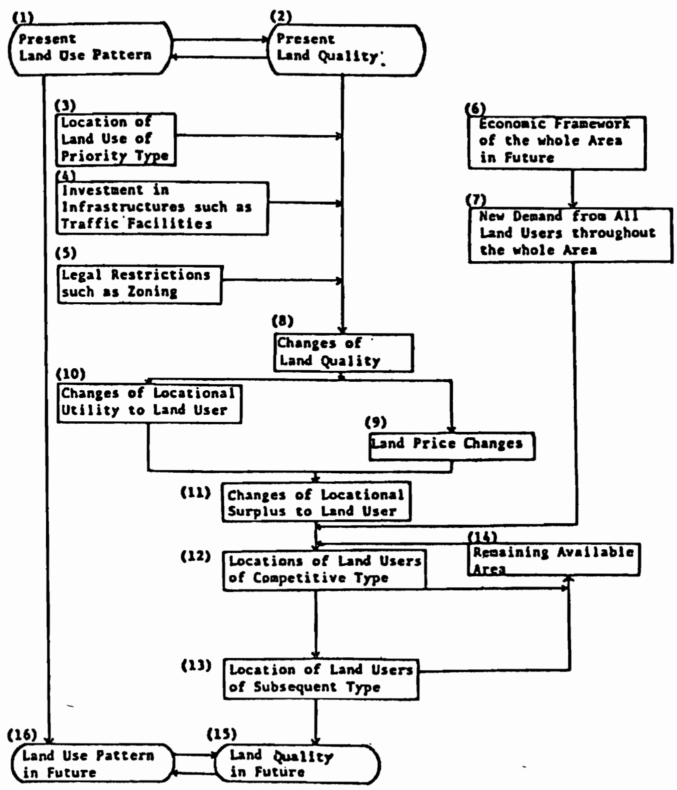


Fig. 3 Model Framework of Changes in Land Use Patterns

The composite pattern of land uses in an area is shown to have an intimate realtion to land quality as we may see from (2) or (16) in Fig. 3. On the other hand, land quality changes greatly (8) when influenced by land uses of priority type, such as large-scale basic industries (3), by investment in such infrastructures as traffic facilities (4), or by legal restrictions such as zoning(5).

This causes changes of land price (9) and of the expected locational utility to land users (10). Therefore the locational surplus to the land user changes (11) and the land user locates at a site (12) which is determined according to locational surplus as well as the intensity of demand (7) of each competing land user.

In this way the amount of area for land uses of the competitive type will change (12) and the area of "subsequent type" will also change proportionally (13). As a result the present land use pattern (1) changes to another pattern (16) in future.

This is the basic idea in our attempt to grasp the process of land use changes, and it is used as the basis for building the land use model to be described in more detail below.

(3) Method for determining lacation of competitive type

The process of determining competitive type locations forms the main part of the land use model.

First of all, the terms used in this paper are defined, and subsequently the method of determining locations will be described.

a) Unit area

This is defined as a zone, of which there are 10 types shown as follows, within a standard square grid (approximately 1 km^2). Unit area is expressed by the composite designation (i,l) of grid i and zone l.

(i) zone for residential use only (class I)
(ii) zone for residential use only (class II)
(iii) primarily residential zone
(iv) neighbourhood commercial zone
(v) commercial zone
(vi) semi-industrial zone
(vii) primarily industrial zone
(viii) zone for industrial use only
(ix) zone of restricted urbanization
(x) rural areas not subject to zoning

b) Average land price at sites of land use k in grid i

The annually "announced" land price is determined according to actual examples of transactions for each land use in each grid during the previous

12 months. Therefore the announced land price is taken as the average land price P_i^k for each land use k within a given grid.

Then land price P_i^k is expressed by a function of indicators giving land quality ${}_mZ_i^k$ as a result of applying quantification theory I.

$$P_i^k = \sum_m \sum_n {}_{mn}\alpha^k \cdot {}_{mn}\delta({}_mZ_i^k) \qquad (1)^{*)}$$

where

${}_{mn}\alpha^k$: score (=weight) of category n of indicator m in relation to average land price P_i^k in a grid of land use k.

${}_{mn}\delta({}_m Z_i^k)$: variable of value 1 when ${}_mZ_i^k$ is in category n ; 0 in other cases.

c) Average of locational utility to land user (k,w) in grid i

It is impossible to measure directly locational utility to each land user at each site. However it can be measured indirectly, through land price functions, by the method described below.

According to the definition of announced land price, it could in theory be supposed that land price P_i^k in function (1) gives the locational utility to a land user with average attributes. For calculation, the locational utility from average levels of land quality can be used instead of imagining a "land user with average attributes".

Then, according to the point of view mentioned above, locational utility of a land user (k,w) in grid i is expressed as below;

$$U_i^{kw} = \sum_m \sum_n {}_{mn}\alpha^k \cdot {}_{mn}\delta({}_mZ_i^{kw}) \qquad (2)$$

U_i^{kw} varies according to the attributes w of land user.

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*) Subscripts and superscripts are defined as follows:

${}_{mn}X_{ilq}^{kw}$

X : variable or indicator

kw : land user of attributes w (e.g., working place, type of industry) engaged in land use k

ilq : site q in zone l of grid i

mn : category n according to the value of land quality indicator m = land quality level

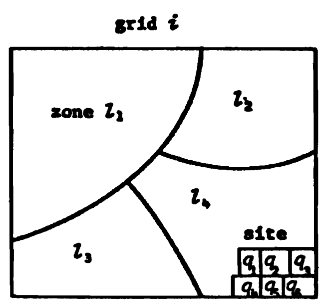

Fig. 4 Relation among grid i, zone l and site q

For example, in case that land use k is housing, indicator ${}_m Z_i^{kw}$ is travelling time to working place w of a commuter living in grid i. On the other hand, ${}_m Z_i^k$ means average travelling time to working places of all commuters living in grid i.

(d) Locational surplus

Locational surplus, a concept which has been mentioned in section 3 (2), is defined as follows.

$$X_{il}^{kw} = U_i^{kw} - P_{il} \tag{3}$$

where

X_{il}^{kw} : locational surplus of land users(k,w) in zone l of grid i

U_i^{kw} : average of locational utility in grid i to land users(k,w)

P_{il} : average land price for all land uses in zone l of grid i, i.e.

$$P_{il} = \sum_k P_i^k \cdot A_{il}^k / \sum_k A_{il}^k \tag{4}$$

where P_i^k is given from function (1) and A_{il}^k is area of land use k in zone l of grid i.

It should be noted that locational surplus is not defined in those zones l where land users (k,w) cannot locate due to zoning restrictions.

e) Distribution of locational surplus due to uncertainty of decision factors

Locational utility U_i^{kw} and land price P_{il} in equation (3) are derived from the land price estimated in chapter 2 according to the definitions given above. As the land price function of each land use is estimated by quantification theory I from a sufficient number of samples, actual values of locational utility and land price distribute normally around the average estimated by functions (2) and (1). These discrepancies are caused by such factors as the unhomogeniety of land quality inside of a grid, the incompleteness of independent variables, actual differences of preference among the individuals who constitute the would-be land users expressed by index (k,w), etc. (which are ignored for purposes of this model). Then locational surplus X_{il}^{kw} can be conceptualized as corresponding to the normal distribution $N(\overline{X}_{il}^{kw}, (\sigma_k)^2)$, i.e.

$$\overline{X}_{il}^{kw} = U_i^{kw} - P_{il} \tag{5}$$

$$(\sigma_k)^2 = ({}^u\sigma_k)^2 + ({}^P\sigma_k)^2 \tag{6}$$

U_i^{kw} : average of locational utility of land users(k,w) in grid i derived from function (2)

P_{il} : average land price of all land uses in zone l of grid i derived from equation (4)

$(\sigma_k)^2$: variance of locational surplus to land users of land use k

$({}^u\sigma_k)^2$: variance of locational utility to land users of land use k *)

$({}^p\sigma_k)^2$: variance of land price of land use k, which is given by the estimated variance of land price function (1)

and

$$f(X_{il}^{kw}) = \frac{1}{\sqrt{2\pi}\,\sigma_k} \exp[(X_{il}^{kw} - \bar{X}_{il}^{kw})^2 / 2(\sigma_k)^2] \qquad (7)$$

Given the fact that D^{kw} is defined as new demand by would-be land users (k,w) in the whole of the area in question and assuming that zones are interchangeable as possible objectives for all would-be land users (except in so far as zoning restrictions interfere), then it can be supposed that D^{kw} is effective in every zone. Therefore, frequency distribution of locational surplus of land users(k,w) in zone (i,l) is expressed by the following function (8).

$$f_D(X_{il}^{kw}) = \frac{D^{kw}}{\sqrt{2\pi}\,\sigma_k} \exp[(X_{il}^{kw} - \bar{X}_{il}^{kw})^2 / 2(\sigma_k)^2] \qquad (8)$$

Fig. 5 is an imaginary example of such values for various type of land users in a number of different zones.

f) Method of calculation

The area Y_{il}^{kw} to be occupied by newly locating land users (k,w) in the case of a given set of values for k and w in zone (i,l) will be defined by the algorithm described below.

It is assumed that the area to be occupied by newly locating users cannot exceed area $^*A_{il}$ available for land users in zone (i,l) and that the surface area newly occupied by users (k,w) throughout the whole region in question is equal to new demand D^{kw}, expressed in area units such as km^2.

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*) It is safely assumed that $E[({}^u\sigma_k)^2] = E[({}^p\sigma_k)^2]$, and thus $({}^p\sigma_k)^2$ is substituted for $({}^u\sigma_k)^2$ in the calculation.

Land use	Land user	Grid: i = 1						-----		i = I_n	
	Zone	Zone for residential use only (class 1) (l = 1)	---	Primarily residential zone (l = 3)	---	Zone for industrial use only (l = 8)	---	-----	---	Commercial zone (l = 5)	---
Single-family houses (k = 1)	Working place No.1 (w=1)		---		---		---	-----	---		---
	⋮	⋮		⋮		⋮				⋮	
Apartment houses (k = 2)	⋮	⋮		⋮		⋮				⋮	
	Working place No.5 (w=5)		---		---		---	-----	---		---
	⋮	⋮		⋮		⋮				⋮	
Central commercial (k = 3)	Central commercial (w=1)		---		---		---	-----	---		---
Industrial (k = 4)	Primal products (w=1)		---		---		---	-----	---		---
	Inter-mediate products (w=2)		---		---		---	-----	---		---
	Final products (w=3)		---		---		---	-----	---		---

Fig. 5 Frequency distribution of locational surplus

$$\sum_k \sum_w Y_{il}^{kw} \leqq {}^*A_{il} \qquad (9)$$

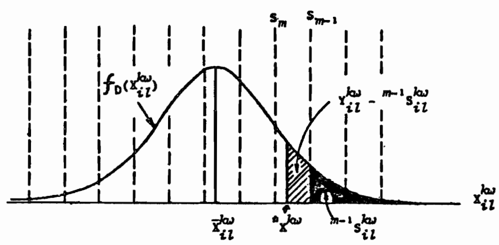

Fig. 6 Relation between locational surplus level and area to be newly allocated

Under this condition, Y_{il}^{kw} will be found according to the assumptions regarding location in section 3(2) by a numerical method based on Fig. 5. Locational surplus level $s_1, \cdots\cdots, s_m$ $(s_1 > \cdots\cdots > s_m)$ is as shown in Fig. 6, and new demand D^{kw} is allocated in sequence $s_1, \cdots\cdots\cdots, s_m$ of sliced locational surplus. Then the following function,

$$F_D(X_{il}^{kw}) = \int_{-\infty}^{X_{il}^{kw}} f_D(X)dX \qquad (10)$$

is defined and X^{kw} is further defined as being equal to $^*X^{kw}$ when all new demand D^{kw} has been allocated. Then, area Y_{il}^{kw} is given as

$$Y_{il}^{kw} = D^{kw} - F_D(^*X^{kw}) \qquad (11)$$

Whenever $^*X^{kw}$ falls between s_m and s_{m-1},

$$^m s_{il}^{kw} = D^{kw} - F_D(s_m) \qquad (12)$$

Hence the area to be newly occupied is determined by the following function:

$$Y_{il}^{kw} = {}^{m-1}S_{il}^{kw} + (D^{kw} - \sum_{i'}\sum_{l'} {}^{m-1}S_{i'l'}^{kw}) \frac{{}^{m}S_{il}^{kw} - {}^{m-1}S_{il}^{kw}}{\sum_{i'}\sum_{l'} ({}^{m}S_{i'l'}^{kw} - {}^{m-1}S_{i'l'}^{kw})} \qquad (13)$$

g) Dynamic changes of location

The description given here is based on a hypothetical example of changes due to new traffic facilities. Let us imagine that commuters living in zone (i,l) are divided into two groups, the first having working place w_1 within convenient commuting distance from grid i and the second having working place w_2 which is inconvenient to reach from grid i. Both groups locate in low density residential sections of zone (i,l), occupying areas A^{w_1} and A^{w_2}, respectively. Assume that a new traffic facility from grid i to working place w_2 is subsequently constructed and comes into operation. Then the locational utility to commuters w_2 to be obtained from zone (i,l) rises greatly and the bid rent rises accordingly. Locational utility (bid price), which is the capitalized value of the average bid rent offered by commuters w_2, continues to rise from the time $t-1$ when the plan of the new traffic facility is made public until time t when it comes into operation, as shown in Fig. 7a. Land price rises are also influenced by this. Therefore the locational surplus of commuters w_2 becomes larger relative to w_1 (Fig. 7b).

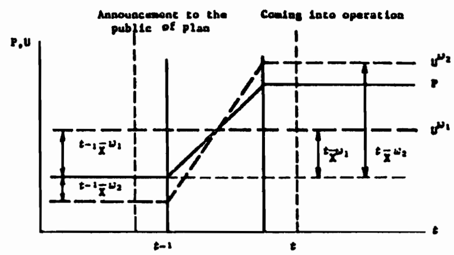

Fig. 7a Changes of locational utility U, land price P and locational surplus X

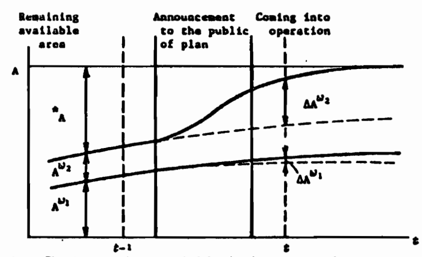

Fig. 7b Area to be occupied by land user w_1 and w_2

It is thought that the influence actually exerted by locational surplus on size of the area to be newly occupied is the difference between the locational utility to land users at time t and land price at time t whose determination is in turn influenced by locational utility at time $t-1$, with the result that there is a time lag between P and U in equation (3). Thus, equation (3) might be rendered more precise by the addition of superscripts t and $t-1$, whereby ${}^{t}X = {}^{t}U - {}^{t-1}P$. Fig. 7b represents a possible result of a location process based on dynamic changes of the locational surpluses of all land users, as shown in Fig. 5. However, for the purposes of the model these changes are observed at two points of time $t-1$ and t, and therefore area

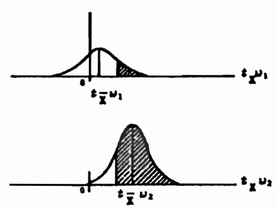
Fig. 7c Distribution of locational surplus of land users w_1 and w_2, considering time lag

Y_{il}^{kw} is derived according to frequency distribution (Fig. 7c) of locational surplus ${}^{t}X^{w}$ which is defined as the difference between ${}^{t}U$ and ${}^{t-1}P$.

The example case mentioned above discusses only two categories of land users, whose working places are different but which compete for the same type of land use (i.e., residential area). But the explanation would be equally true in the case of many land use categories and many land users competing simultaneously.

(4) Applicability of the model

To test applicability, actual changes from 1965 to 1975 were observed in a suburban area of Tokyo (between Tokyo and Yokohama) which consists of 123 grids (= approximately 13,000 ha) and where a new rail line came into operation in 1966, with the result that residential land use increased greatly during the decade.

Test input data used in the model are as follows:

i) Distribution of existing land uses in 1965
ii) Distribution of land uses of priority type in 1975
iii) Land quality changes of each grid due to new construction of railways and main roads, equipment of gas supply facilities and sewerage
iv) Zoning restrictions
v) Unit area of each land use of subsequent type in proportion to other types
vi) Changes in area of each land use from 1965 to 1975 in the whole of the test area (These changes are taken to correspond to demand D^{kw}.)

Fig. 8 shows both actual and estimated changes of distribution of residential area within the test area. In this case, w_1 is Yokohama, and w_2 is Tokyo. Fig. 8 shows that many commuters to Tokyo proceeded to locate within the test area as the locational utility to them rose greatly after the opening of the new rail line. The model simulated well such changes as the large increases of commercial areas mainly in front of stations, surrounded by new residential areas, whose development was begun somewhat earlier than that of the new commercial areas. The model also simulated well increases of industrial areas near freeway interchanges. Correlation coefficients proved to be 0.912 for residential areas, 0.794 for commercial areas, and 0.977 for industrial areas.

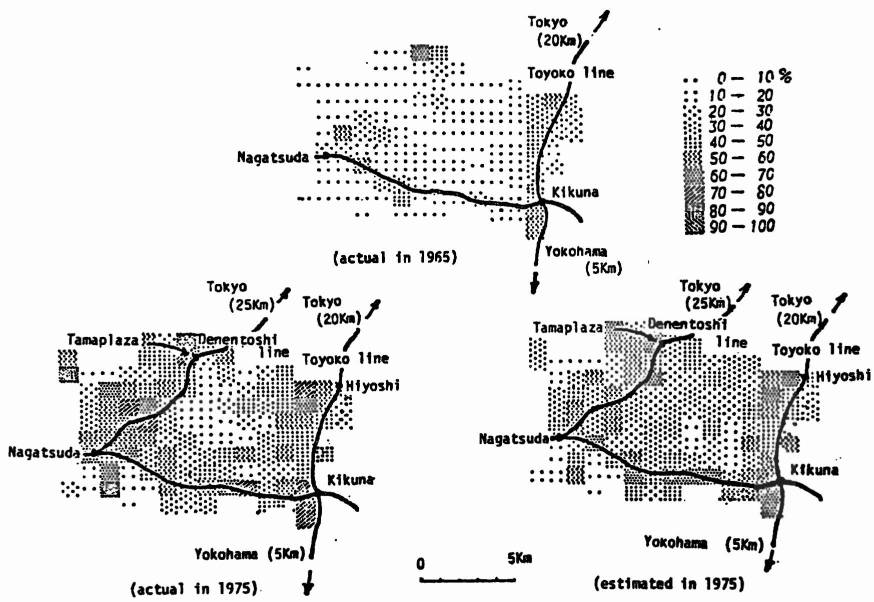

Fig.8 Changes of residential areas in a suburban area of Tokyo

4. Acknowledgement

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