BACKCASTING ANALYSIS OF LOCATIONAL INTERACTIONS BETWEEN BUSINESS SECTORS

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Abstract: Though many researchers have tried to find sustainable urban forms, the methods have not yet been developed enough. In this study, we develop a method of backcasting analysis utilizing a land-use and transport model with a particular focus on business location. First, we develop a business location sub-model with a mechanism of locational interactions between business sectors, based on a model framework proposed by Tomita, Terashima, Hammad and Hayashi (2003). Second, after comparing "forecasting analyses" and a "backcasting analyses", a model for backcasting analysis together with a calculation algorithm is developed, based on the algorithm of Fowkes et al (1998) for a strategic transport model.

Keywords: backcasting analysis, sustainable city, land-use and transport model, business location

1 INTRODUCTION

Many researchers have tried to find sustainable urban forms. Newman and Kenworthy (1989) showed that the higher a population density in a city is, the less its transport energy is consumed, through an empirical study using statistical data of many cities throughout the world. However they have not discovered what urban forms are convenient for people and sustainable for the global environment. The aim of this paper is to develop a method to search for convenient and sustainable urban forms for individual cities on a platform of GIS.

First, based on the framework of an integrated land-use and transport model by Tomita, Terashima, Hammad, and Hayashi (2003), a business location sub-model with a mechanism of locational interactions between business sectors is developed by means of spatial interaction models.

Second, after comparing “forecasting analyses” and “backcasting analyses”, a model for backcasting analysis together with a calculation algorithm is developed. This model is formulated as a mathematical programming model. Using our model, we can obtain an optimal spatial distribution of employment by sector under a set of sustainable constraints such as limits on energy consumption and CO_2 emission, etc.

2 FRAMEWORK OF THE INTEGRATED LAND-USE AND TRANSPORT MODEL AND BUSINESS LOCATION SUB-MODEL

2.1 Framework of the integrated land-use and transport model

Integrated land-use and transport models have been developed for forty years since the Lowry Model (1964) and used for analyses for making structural plans of land-use and transport. These models have been reviewed in several papers (Webster et al., 1988; Wegener, 1994; Miller et al., 1998). A model by Tomita, Terashima, Hammad and Hayashi(2003), whose framework is shown in Figure 1, is one of the examples. This model consists of five sub-models: (1) business location sub-model, (2) residential location sub-model, (3) land price sub-model, (4) transport sub-model, and (5) environment sub-model. These sub-models are outlined as follows.

(1) Business location sub-model

The outputs of this sub-model are spatial distributions of employment by business sector. The sub-model is formulated as a spatial interaction model that has a mechanism of inter-sector locational interaction. The explanatory variables are accessibilities to population and economic activities.

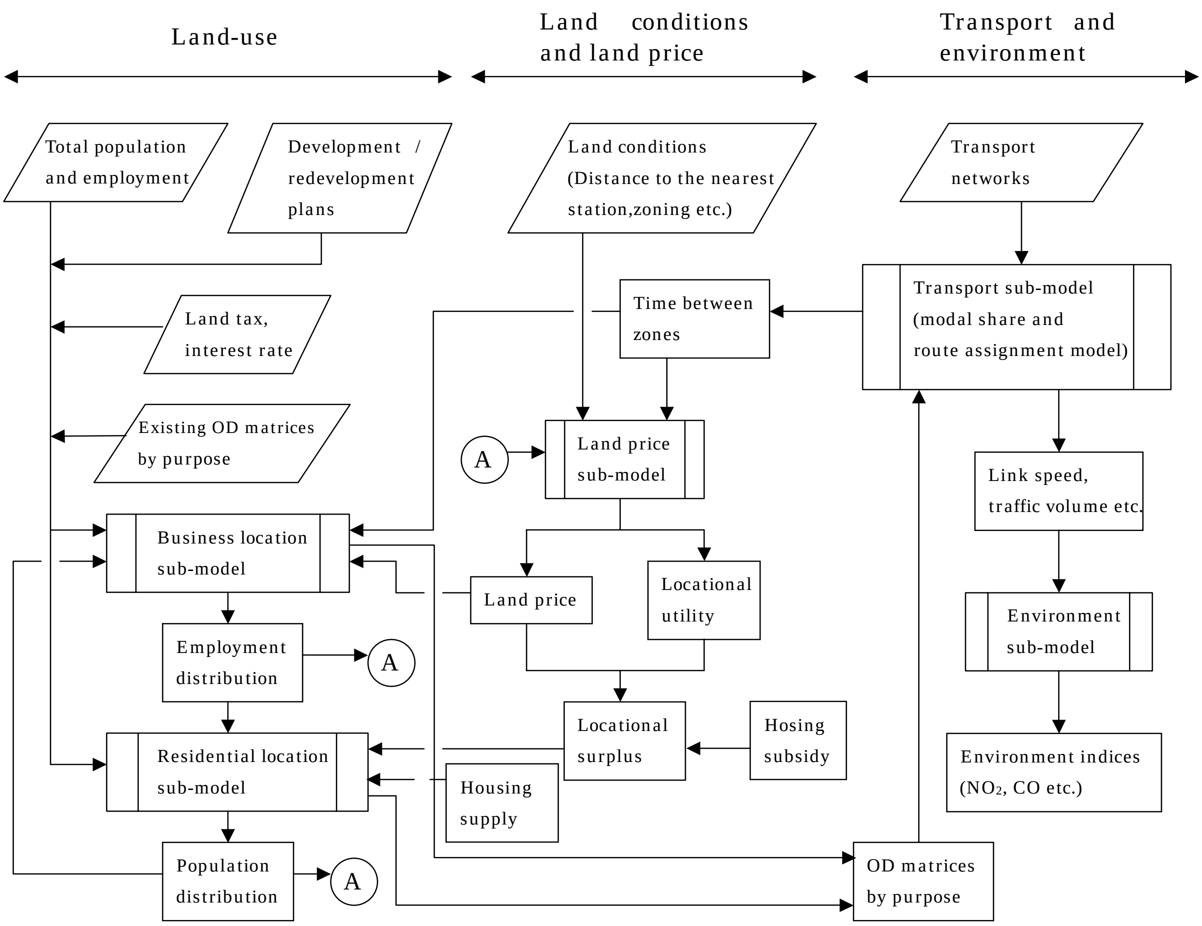

Figure 1 Model Framework

(2) Residential location sub-model

The outputs of this sub-model are a spatial distribution of population. The sub-model is formulated by applying a disaggregate logit model (Hayashi and Tomita, 1990), which simulates a household's residential decisions from migration to residential location choice sequentially. Its major explanatory variable is "Locational Surplus" (Nakamura, Hayashi and Miyamoto, 1983).

(3) Land price sub-model

The outputs of this sub-model are land prices. These are then aggregated into average land price in each zone. This sub-model is formulated by a "random bidding model" (Lerman and Kern, 1983), which is based on an assumption that the highest random bid is realized as the land price. Using this sub-model, the locational surplus in the above residential location sub-model is also measured. The explanatory variables of this sub-model are land conditions such as accessibility to a work-place, distance to the nearest railway station, and dummy variables of land readjustment etc.

(4) Transport sub-model

The outputs of this sub-model are daily average vehicle speeds and traffic volumes on road links. First, the OD matrices by purpose are estimated by using the accessibility indexes from the residential and business location sub-models. Then modal split and traffic assignment trips are predicted by using a standard urban transport model.

(5) Environment sub-model

In this sub-model, using vehicle speeds and traffic volumes given by the above transport sub-model, the NOx, CO, CO_2 emissions and energy consumption on road links are estimated.

2.2 Business location sub-model with a mechanism of locational interactions between sectors

(1)Basic equation

This business location sub-model is a spatial interaction model with a mechanism of locational interactions between sectors, which is formulated as shown in Equation (1). In the equation, the number of employee (E_i^k (*t+1*))) of sector (*k*) in zone (*i*) at a future time (*t+1*) is explained by the number of employees for the intermediate product and that for the final product, which accord with the first term and second term in Equation (1) respectively. This sub-model can analyze the effects of transport network policies, new town policies, and land tax policies. Transport network policies affect $S_{ji}^{mk}(t)$ $S_{ji}^{k*}(t)$ through changes of transport costs and times between zones. New town policies and land tax policies affect $P_j(t)$ and T_i^k respectively.

$$E_i^k(t+1) = \alpha_k \sum_m \theta_m^k \left(\sum_j E_j^m(t)\, S_{ji}^{mk}(t+1)\right) + \beta_k \sum_j P_j(t)\, S_{ji}^{*k}(t+1) - T_i^k \qquad (1)$$

where

$E_i^k(t)$: Number of employees of sector (*k*) in zone (*i*) at a time (*t*)

θ_m^k : Ratio of number of employees in sector (k) to total number of employees required in production of sector (*m*)

$S_{ji}^{mk}(t)$:Ratio of number of emplyees in sector (*k*) in zone (*i*) to total employment required for production of sector (*m*) in zone (*j*) at a time (*t*)

$P_j(t)$: Population in zone (*j*) at a time (*t*)

$S_{ji}^{*k}(t)$:Ratio of volume traded with households in zone (*j*) to total production of sector (*k*) in zone (*i*) at a time (*t*)

T_i^k : Additional land tax to sector (*k*) in zone (*i*), which is converted to number of employees by average wage of sector (*k*)

α_k , β_k : Parameters of sector (*k*)

Moreover three variables (θ_m^k , S_{ji}^{mk} , S_{ji}^{*k}) in the above equation are formulated as follows. The vaiable (θ_m^k) is the ratio of employment in sector (*m*) to total employment number required in production of sector (*k*), which is given as the following equation.

$$\theta_m^k = \omega_{mk} / \sum_k \omega_{mk} \tag{2}$$

where

ω_{mk} :Trade amount between sectors (*m, k*) by workforce unit of sector(*m*), which is defined as $\omega_{mk} = X_{mk}/(E_m/TX_m)$ where X_{mk} is the amount traded between sectors (*m,k*) in monetary units. E_m is the number of employees of sector (*m*), and TX_m is total production of sector (*m*) in monetary units.

Then, another variable (S_{ji}^{mk}) is the ratio of number of emplyees of sector (*k*) in zone (*i*) to total employment required for production of sector (*m*) in zone (*j*), and the other variable (S_{ji}^{*k}) is the ratio of volume traded with households in zone (*j*) to total production of sector (*k*) in zone (*i*). These variables are formulated as shown in equations (3) and (4) applying spatial interaction models.

$$S_{ji}^{mk} = E_i^k(t+1)\, exp(-\gamma^k t_{ji}) / \sum_i E_i^k(t+1)\, exp(-\gamma^k t_{ji}) \tag{3}$$

$$S_{ji}^{*k} = E_i^k(t+1)\, xp(-\delta^k t_{ji}) / \sum_i E_i^k(t+1)\, exp(-\delta^k t_{ji}) \tag{4}$$

where

$E_i^k(t+1)$: Number of employees of sector (*k*) of zone (*i*) at a time (t+1)

t_{ji} : Generalized cost between zones (*j, i*)

γ^k, δ^k : Distance resistance parameters of sector (*k*)

(2)Constraints

In simulating by utilizing the above basic equation (1), a constraint in number of employees due to available area of land in each zone is shown by the following equation.

$$\sum_k E_i^k(t+1) \le E_i^{total} \tag{5}$$

where

E_i^k : Number of employees of sector (*k*) in zone (*i*) at a time (t+!)

E_i^{total} : Accepted maximum total number of employees in zone (*i*)

Then, the total number of employees summed up in all zones by sector is assumed, which is shown in the following equation.

$$\sum_i E_i^k(t+1) = E_{total}^k \tag{6}$$

where

E_i^k : Number of employees of sector (*k*) in zone (*i*) at a time (t+1)

E_{total}^k : Total number of employees of sector (*k*) in all zones

3 MODEL FOR BACKCASTING ANALYSIS AND ITS CALUCULATION ALGORITHM

3.1 Forecasting analyses vs. backcasting analyses

In forecasting analyses, predictive models are utilized. The process of analysis is as follows: firstly, policy alternatives must be well examined and selected; then the effects of each policy alternative are estimated by utilizing predictive models; finally an optimal policy alternative is determined. These analyses are suitable in growing cities without meeting severe constraints such as environments, government finances, and natural resources.

On the other hand, in backcasting analyses, normative models are utilized. In these analyses, optimal policies are directly determined by optimizing objective function under given constraints without selecting policy alternatives. The constraints include the following: 1) natural resource and environment constraints (for example, upper limit of energy consumption), 2) financial resource constraints (for example, upper limits of transport network improvement etc.), 3) equity constraints (for example, upper limit of average commuting time by zone), 4) constraints of the behavioural mechanism of the system (which are formulated in predictive models).

In recent years, backcasting analyses become more important than forecasting analyses, because constraints become severer. However, as the backcasting analyses are formulated as a complicated mathematical programming model, it is difficult to solve the problem utilizing the usual computational algorithm. Therefore a computational algorithm for the backcast analysis is developed in section 3.3.

3.2 Model for backcasting analysis and its characteristics

A model for the backcating analysis is formulated as a mathematical programming model with an objective function and constraints. In this paper, the objective function is total travel cost (generalized cost) which consists of a commuting travel cost and a business travel cost, and the constraints include the following: 1) equations of business location sub-model, 2) total number of employees by sector, 3) accepted maximum number of employees by zone, and 4) total transport energy consumption etc., These are formulated as follows.

$$TC(X) = CTC(X) + BTC(X) \rightarrow \text{Min} \quad (7)$$

s.t.

$$TEC(X) \leq EC^{max} \quad (8)$$

and Equations (1)- (6)

where

$TC(X)$, $CTC(X)$, $BTC(X)$: Total travel cost, commuting travel cost, and business travel cost respectively in the case of a vector of policy variables (X).

$TEC(X)$: Total transport energy consumption in the case of a vector of policy variables (X).

EC^{max}: Accepted maximum amount of total transport energy consumption

In the above equations, a vector of policy variables (X) consists of generalized travel costs (t_{ji} :) in Equations (4) and (5), and land taxes (T_i^k) in Equation (1).

Then in order to consider the model's characteristics, the transport costs in the following two cases of businesses locations are compared: 1) "centralized pattern to city centre" and 2) "decentralized pattern to suburban" are compared under conditions that transport network and population distribution are given. In respect of commuting travel costs, the decentralized pattern is superior to the centralized pattern. On the other hand, in respects of business travel costs, the centralized pattern is superior to the decentralized pattern. Therefore, an optimal locational pattern and an optimal policy exist.

3.3 Calculation algorithm

Fowkes et al. (1998) developed a short-cut method to optimize transport policy based on a limited number of model runs together with a regression equation between a value of the objective function and values of policy variables, without simulating all of the policies. However, this method does not use the information efficiently because it uses a *single-variable* quadratic regression equation that cannot capture synergic effects among policies efficiently. To capture these effects, we modified this method by introducing a *multi-variable* quadratic regression equation, which is more efficient than the original *single-variable* equation.

This procedure is illustrated in Figure 2 and summarized in Figure 3. First, some policies are selected randomly from the policy sphere around the optimal policy, referring to the sensitivity analysis of each single policy (Step 1). Each selected policy is simulated and the value of the objective function is estimated using the business location sub-model (Step 2). Figure 1 illustrates the relationship between the value of the objective function and values of policy variables. This relationship is determined by a multi-variable quadratic regression equation (Step 3). Using the regression equation, an approximate optimal policy can be determined as illustrated in Figure 2 (Step 4). This approximate optimal policy is then evaluated using the business location sub-model (Step 5) and a convergence test is applied on the values of the objective function and policy variables (Step 6). The value of the objective function can be improved by recursively iterating the above process around the approximate optimal policy through narrowing the policy sphere of selected policies at the beginning of the iteration.

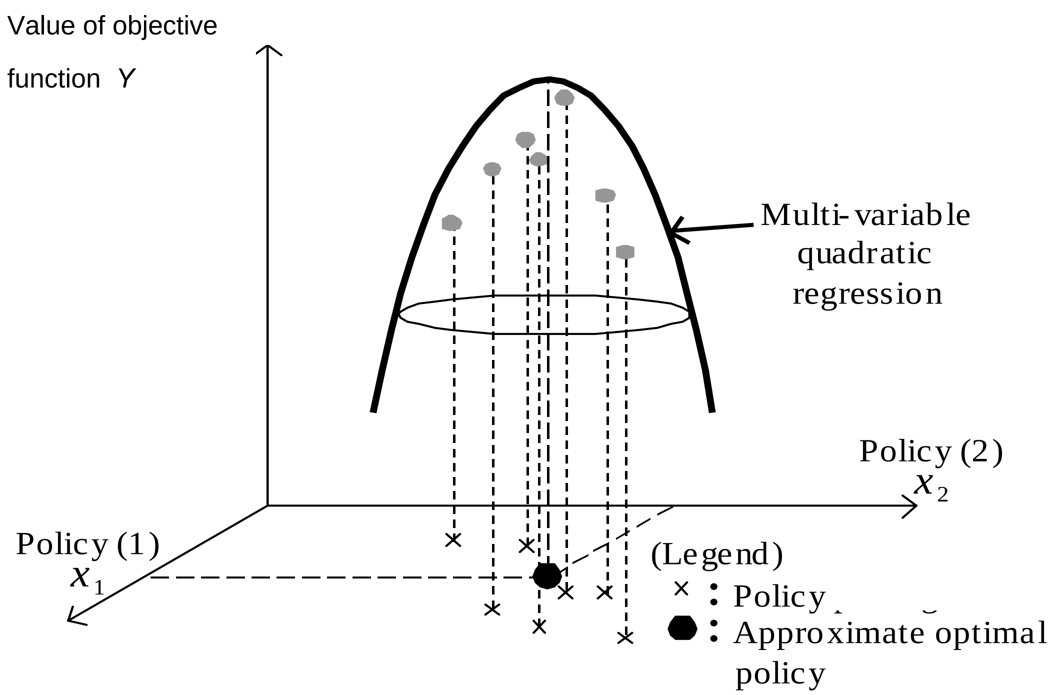

Figure 2 Multi-variable Quadratic Regression and Approximate Optimal Policy

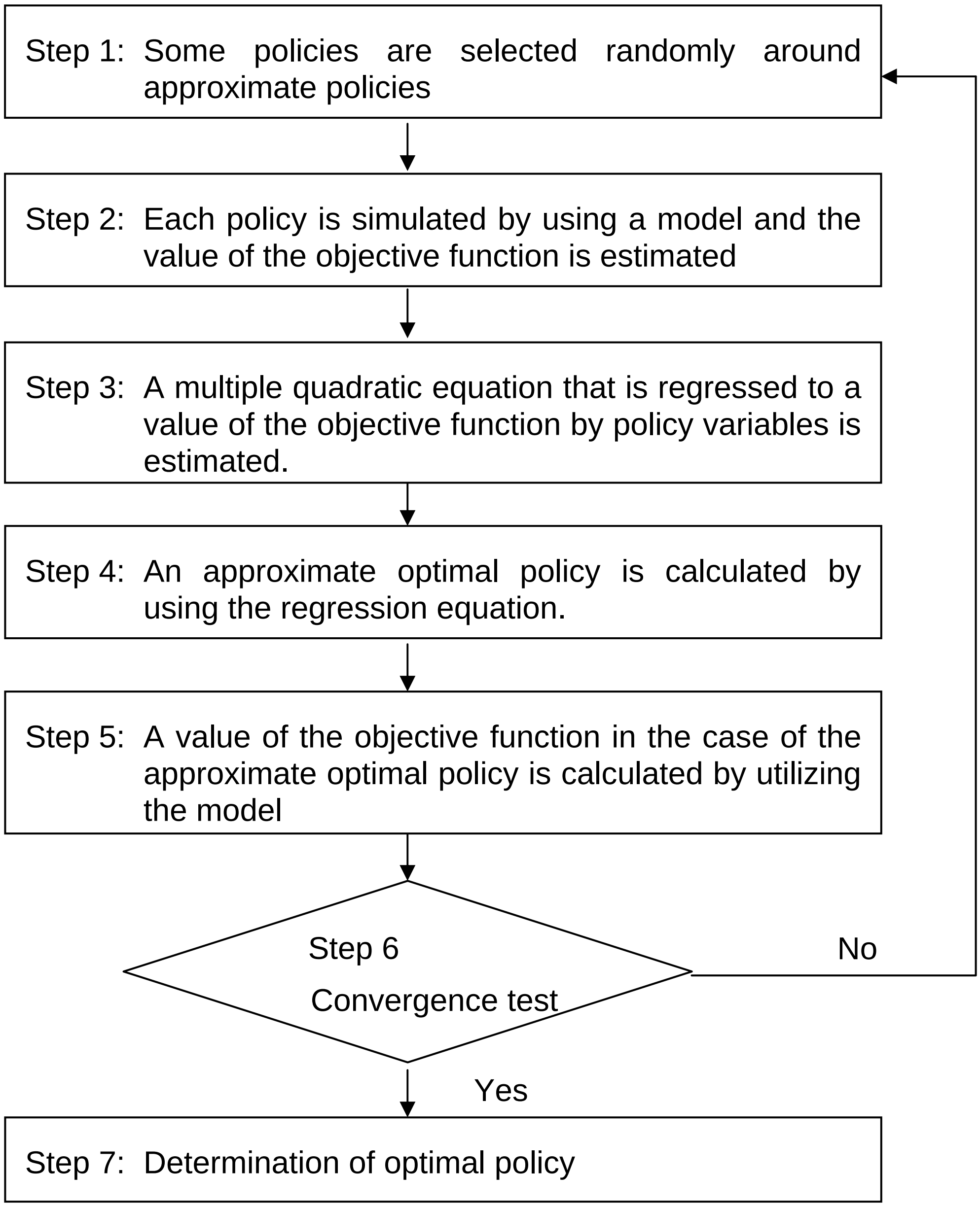

Figure 3 Procedure for Determining Optimal Policy

4 Conclusions

In this paper, based on the framework of the integrated land-use and transport model by Tomita, Terashima, Hammad and Hayashi (2003), a business location sub-model with a mechanism of locational interactions between business sectors was developed.

In addition, a mathematical programming model for backcasting analysis utilizing business location sub-models in order to find an optimal spatial distribution of employment and a policy to realize it was drafted. For the calculation of the above model, an algorithm was developed referring to Fowkes's method (1998), whose algorithm could also be utilized for solving other mathematical programming models which can not be solved by the usual optimization algorithm.

In the near future, the developed business location sub-model and the backcasting analysis should be applied to real cities.

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