【土木計画学研究・論文集 No.16 1999年9月】

NETWORK EVOLUTION WITH COST-BENEFIT EVALUATION RULES*

Mehmet Ali TUNCER**・Morimitsu KURINO*** Kiyoshi KOBAYASHI****

1. INTRODUCTION

Small events in history may create a formation of an urban system different from the one that exists today. Especially, the locational patterns of face-to-face communication intensive agents such as knowledge firms, management functions, etc., follow paths that depend upon history[1]. Agglomeration economies introduce an indeterminacy; when agents and firms want to congregate where others are, one or a few locations may end up with the large share of entire population. If we bypass this indeterminacy by arguing historical accident for the dominant locations, we must define historical accident and how they act to select the winning locations.

The spatial economic literature tends to see the spatial ordering of cities as the economic response to geographical endowments, especially transport possibilities. The locational pattern is an equilibrium outcome of individual decisions. In this view locational history is not a matter to the extent that the equilibrium outcome is unique; the locational system is deterministic and predictable. Recently, alternative new views has come up to see that agents' locations are as path-dependent as an organic process with new agents laid down upon and very much influenced by inherited locational patterns already in place. Geographical differences and transport possibilities were important, but here the main driving forces were agglomeration economies, the benefits of being close to other agents. Later comers might be attracted to these same places by the presence of these early locators, rather than geography.

Agglomeration of population, once the positive feedback process are geared in, has the nature of a cumulative self-reinforcing process because the emergence of a particular location as a major agglomeration city does not only depend upon the intrinsic nature of this site. In other words, historical matters such as the sequences of network formation appear to be essential in the selection of a particular equilibrium. Minor changes in the sequences of network formation at some critical periods may well results in very different geographical configuration[2)-6)].

This paper attempts to provide some experimental examples for the historical policy driven agglomeration by revealing how city systems evolve through time in response to policy initiatives for network formation. In particular, it examines the dynamics of population location using a simple general equilibrium model with agglomeration economies that permits a description of the lock-in effects associated with existing agglomerations. By assuming that the government applies slightly different decision rules (cost-benefit evaluation rules) and that it improves the transport network, especially the railway network, through one by one link improvements in the order that the links with the highest benefit-cost ratios are given the highest priority to be improved, this paper tries to demonstrate that city systems will evolve in such a manner that population will indeed cluster in some dominant locations, and that this depends both on the geographical conditions and historical order of network improvement.

2. SCOPE OF THE STUDY

(1) Previous Studies

Many authors[7)8)] have analyzed general equilibrium effects of inter-city transportation investment. These studies specified *a priori* the industrial structure of each city and trade pattern, which is a restrictive assumption for city size distribution that is one of the objective of this study. Urban economists have developed models explaining how the size of each city is determined in the system of cities[9)10)]. However, these models have not considered spatial factors at the inter-city level, such as location of cities, distances, or transport costs between them. Krugman[11)] analyzed

*Keywords: Cost-benefit analysis, Regional Planning
**Student member of JSCE, M.Eng., Graduate School of Civil Eng, Kyoto University, Kyoto 606-8501, TEL・FAX 075-753-5073
***Student member of JSCE, M.Eng., Graduate School of Civil Eng, Kyoto University, Kyoto 606-8501, TEL・FAX 075-753-5073
****Regular member of JSCE, Dr.Eng., Graduate School of Civil Eng, Kyoto University, Kyoto 606-8501, TEL・FAX 075-753-5071

industrial location by incorporating transport costs into the multi-region model of interregional trade with scale economy. Concentration of production activities may occur even when all regions are homogeneous and no comparative advantage exists. Several authors[5)6)] further developed models so that the economy has multiple industrial sectors, and analyzed a dynamic process of city formation and development. They demonstrated that as an economy's population size increases, the urban system organizes itself into a Christaller-type hierarchical system. There has been extensive literature about computable general equilibrium models[12)13)]. There is an increasing number of general equilibrium modeling which allow increasing returns to explain the formation of city systems. Among others, Mun presented a tractable general equilibrium model with increasing returns caused by interactions between agglomeration economies and transport network structure in city systems[14)]. Kobayashi and Okumura[15)] investigated a dynamic multi-regional growth model with spatial agglomeration, where major concern is upon interregional knowledge spillover. In this study, a simple general equilibrium model is presented to provide some insights into the impacts of decreasing distances among cities upon economic geography. The model presented in this paper highlights one of the major sources of increasing returns, i.e., spatial agglomeration generated through technological externalities in production. The model is designed to exclusively simulate how the structure of city systems will evolve in response to railway network improvement. Compared with the previous studies, the model is rather simple, but sufficient to simulate how interactions via railway transportation lead to the endogenous formation of dominant cities on the networks.

(2) System Evolution and Path-Dependency

In the previous literature, there has been two types of externalities in shaping spatial agglomeration discussed: peculiar and technological externalities[5)]. The former is the externality which appears through market transactions. For example, more and more population want to agglomerate because of the various factors that allow a larger diversity and the wider array of human interactability for consumption. Cities are typically associated with a wide range of products and a large spectrum of public services so that consumers can reach higher utility levels and have stronger incentives to migrate towards cities. The latter is associated with the advantage of proximity in communications. Setting up of new links in transport networks gives rise to new incentives for people to migrate because they can expect better business chance. This in turn makes the place more attractive to production agents which may expect the advantage of getting knowledge and ideas they need. This idea has been well expressed by Marshall[16)]. As pointed out more recently by several authors[17)18)], human contacts among individuals sharing common interests can be a vital input to creativity. In this respect, it is well known that face-to-face communications are most effective. In this paper, we exclusively focused upon the latter types of externality to describe how city systems will evolve in response to increasing possibilities of face-to-face communications due to railway network improvements.

The path-dependency is omnipresence for the evolutionary patterns of city systems. Given that cities grow largely due to self-enforcing advantages of agglomeration economies, their very presence generates the lock-in effect in the location space. The lock-in effect is the reason why a city can still prosper even after the disappearance of distance friction. The structure of the urban system is not determined freely; rather due to the lock-in effect of the urban systems as a whole, its structure tends to follow the power of inertia. However, the strong presence of inertia in the structure of the urban system does not necessarily deny the chance of the structural change in the long run. The transport network is the means to keep the power of inertia, but it may also provide chances for the city system to change its structure. There is the circular causation between spatial agglomeration of population and network improvement decisions through forward-linkages (an increased interactability due to network improvement enhances spatial agglomeration) and backward-linkages (spatial agglomeration needs more network investment). Through these linkage effects, scale economies at a certain location start to function, and are transformed into increasing returns at the level of the city system as a whole. The spatial ordering is not unique when these types of scale economies are functioning in locational fields. Early agglomeration and/or link formation put down by historical accident on the network; the subsequent locational and investment decisions are regulated by their presence. A different set of early events could have steered the network pattern into a different outcome, so that development history is crucial. Because of the existence of multiple equilibria, minor changes in historical events, i.e., the sequences of the network improvement in the context of this paper, may generate dramatic changes in the equilibrium network geography in the long run. This suggests that historical matters explain actual city patterns and that circular causation generates a snowball effect that leads city systems to be locked in within the same region for long time periods[4)].

3. THE MODEL

(1) Assumptions

An economic system of n cities, indexed by $i = 1, 2, \cdots, n$, is considered, where the cities are connected by a railway transportation network. The economy produces one type of commodity consumed by the whole population and the transportation sector. Perfect competition is assumed to prevail in good markets both within each city and between cities. To avoid unnecessary complications, we consider economies without capital. This assumption is strong since it implies that cities form autarky economies; no trade is needed between cities. At the sacrifice of trade possibility, we can gain analytical tractability and investigate solely the interactions between city formation and face-to-face interactability via railway transport. The population is homogeneous and freely mobile among cities, whereas multi-habitation and inter-city commuting are not allowed. The assumption of perfect free mobility will be relaxed in 4. and 5. Furthermore, the total population of the whole system is given exogenously at any point in time, and is constant.

Each city is geographically monocentric, and consists of two parts, the central business district (CBD) and residential area. The city residents commute to the single CBD by intra-city railway systems, and pay for the commuting. For simplicity, we assume that each CBD is a point and all production activities are concentrated in the CBD of the respective cities. Production agents employ only the labor force, and local labor force is fully employed in their respective markets. Land is assumed to be owned collectively by all residents through shares in a local land bank. The land bank pays out dividends to local residents which normally equals the average per capita land rent paid out. There is no agricultural land available, which means that the land price is zero at the edge of the city. Residential area is divided into land lots a la Henderson[9], whose areas are fixed to the same size regardless of their location. The households achieve the same utility levels regardless of the location in which they live. The central government controls the travel costs between cities by improving the existing railway connections according to cost-benefit analysis. The government does levy uniform lump-sum taxes on all households to fully finance the network improvement. The model formulated below comprises urban economics model to describe urban land use patterns of the respective cities and a general equilibrium model to characterize the whole economy of the city system. The size, land use patterns, and production capacities of respective cities, the so-called economic geography, are endogenously calculated at each step given the spatial distribution of population of the whole economy.

(2) Urban Economic Model

Consider the representative household residing at a point with distance u_i from the CBD of city i. The utility function is regulated by both composite commodity consumption $x_i(u_i)$ and housing lot size $l_i(u_i)$, being fixed to $l_i(u_i) = 1$. With a budget constraint, the composite commodity consumption is given by

$$x_i(u_i) = y_i - p_i(u_i) - c_i u_i - \tau \tag{1}$$

where y_i is income, $p_i(u_i)$ is the land rent per unit lot size at point u_i, and c_i is the cost of commuting per unit distance that is constant everywhere in the city, τ is the lump-sum tax to be levied by the government to finance the network improvement. The tax is uniformly levied across the whole system. With the Cobb-Douglas utility function $x_i(u_i)l_i(u_i)^{\iota}$ where ι is a parameter, the indirect utility function is

$$V_i(u_i) = y_i - p_i(u_i) - c_i u_i - \tau. \tag{2}$$

Since all households will get the same utility regardless of their location, the spatial condition gives us $\partial V(u_i)/\partial u_i = 0$. From equation (2) it can be seen that increased transport costs with increased commuting costs are offset by reduced rents, thus we have $\partial p_i(u_i)/\partial u_i = -c_i$. From the assumption, that there is no agricultural land use, there holds $p_i(L_i) = C_0 - c_i L_i = 0$ at the edge of the city where $u_i = L_i$. Integrating the equation $\partial p(u_i)/\partial u_i = -c_i$ we have the land gradient given by

$$p_i(u_i) = c_i(L_i - u_i). \tag{3}$$

The utility level of the household at the city edge, $u_i = L_i$, is

$$V_i = y_i - c_i L_i - \tau \tag{4}$$

which is also equal to the utility level for all households regardless of their location within the city. Given the fixed lot size over the economy, the size of city i can be defined by the area of urban land use. Thus,

$$N_i = \int_0^{L_i} 2\pi u_i du_i = \pi L_i^2. \tag{5}$$

By integration, the aggregate demand function, F_i can be described by

$$F_i = \int_0^{L_i} 2\pi u_i x_i(u_i) du_i = N_i(y_i - c_i \pi^{-\frac{1}{2}} N_i^{\frac{1}{2}}). \tag{6}$$

Similarly, we can get the aggregated land rents, P_i, and transportation costs, T_i, over the population of city i by

$$P_i = \int_0^{L_i} 2\pi u_i p_i(u_i) du_i = \frac{1}{3} c_i \pi^{-\frac{1}{2}} N_i^{\frac{3}{2}}, \tag{7}$$

$$T_i = \int_0^{L_i} 2\pi c_i u_i^2 du_i = \frac{2}{3} c_i \pi^{-\frac{1}{2}} N_i^{\frac{3}{2}}, \tag{8}$$

respectively. The equilibrium utility levels of the representative household can be fully characterized by the four parameters, y_i, N_i, c_i: and τ:

$$V_i = y_i - c_i \pi^{-\frac{1}{2}} N_i^{\frac{1}{2}} - \tau. \tag{9}$$

Let us next define the behavior of the firms. We will assume a constant return to scale technology and use the production function of the form[15)]

$$Y_i = N_i^{\alpha} \left\{ \sum_j N_j \left(\frac{R_{ij}}{N_j} \right)^{\xi} \right\}^{\gamma} \tag{10}$$

where Y_i is total output, R_{ij} is the inter-city communication frequency between city i and j, and α, ξ, γ are parameters satisfying $\alpha + \xi\gamma = 1$. The production function, (10), indicates that the cities have identical production technology but different potential for human contacts. The frequencies of interaction among cities are endogenous in the model. Since the factor demands for production are determined by perfect competition, equating the marginal products of the labor force and the frequency of inter-city communication respectively to the wage rent, w_i, and the transportation cost between nodes i and j, d_{ij}, we get the following conditions:

$$w_i = \alpha \frac{Y_i}{N_i}, \qquad \text{and} \qquad d_{ij} = \frac{\gamma\xi Y_i}{R_{ij}} \frac{N_j \left(\frac{R_{ij}}{N_j} \right)^{\xi}}{\sum_k N_k \left(\frac{R_{ik}}{N_k} \right)^{\xi}}. \tag{11}$$

From the second condition of (11), we directly see that

$$R_{ij} = \left\{ \frac{\gamma\xi Y_i}{d_{ij}} \frac{N_j^{1-\xi}}{\Phi} \right\}^{\frac{1}{1-\xi}} \qquad \text{and} \qquad \Phi = \sum_k N_k \left(\frac{R_{ik}}{N_k} \right)^{\xi}. \tag{12}$$

By substituting the first equation of (12) to the second one, we have

$$\Phi = (\gamma\xi Y_i)^{\xi} \left\{ \sum_k N_k d_{ik}^{-\frac{\xi}{1-\xi}} \right\}^{1-\xi}. \tag{13}$$

Thus, from (12) and (13), we see that the inter-city communication frequency, R_{ij}, is described by a gravity model:

$$R_{ij} = \gamma\xi Y_i \frac{N_j d_{ij}^{-\frac{\xi}{1-\xi}}}{d_{ij} \sum_k N_k d_{ik}^{-\frac{\xi}{1-\xi}}}. \tag{14}$$

From (7) and (11), the household income is given by

$$y_i = w_i + \frac{P_i}{N_i}. \tag{15}$$

In this model the transportation sector is implicit. Transportation sector is assumed to be run by non-profit firms. No labor is employed. The sector produces transportation services by utilizing economies' outputs. The firms pay for consumption of transportation services. The revenue of inter-regional transportation sector is balanced with its factor payments. On the contrary, the revenue of intra transportation services leaks from the economy. The more population concentrates to a single city, the more leakage of the revenue occurs due to the increase of city size. This is the negative effect of agglomeration upon the economy of the city system. The central government also consumes economies' outputs to improve the railway network. The improvement cost is fully financed by the tax revenue from the households.

(3) Equilibrium Conditions

The wage rate w_i of a particular city is determined so that the supply and demand for the labor force is brought into equilibrium. The population distribution among cities can be brought into equilibrium when no household has incentive to move. Thus, the equilibrium of population distribution can be characterized by

$$\begin{aligned} V_i &= \overline{V} \quad if\ N_i > 0 \\ V_i &\leq \overline{V} \quad if\ N_i = 0 \end{aligned} \tag{16}$$

for i $(i = 1, \cdots, n)$, where $\overline{V}$ is the equilibrium utility level. At this point it is important to note that the equilibrium utility levels are only calculated for the cities which have positive population. The city, where people cannot attain the equilibrium utility level, dies. The city population satisfies the adding-up constraint:

$$\sum_{i=1}^{n} N_i = N, \tag{17}$$

where N is the exogenously given total population of the system. In the model described above, N, c_i, and d_{ij} are the exogenous variables, whereas $\overline{V}$, V_i, u_i, P_i, y_i, N_i and R_{ij} are the endogenous variables.

4. STRUCTURE OF SIMULATION EXPERIMENTS

(1) The Objectives

The major objective of the simulation experiments is to investigate how the network evolution is regulated by the history of policy initiatives for network improvement. In the experiments, the network evolution refers to the dynamic change of the city systems driven by the successive construction of new links, or of improvement of the existing links that connect the cities. The cost-benefit evaluation rules are highlighted as the policy initiatives to determine the successive order of the network improvement. As explained in **2.(3)**, when the circular causation between locational and investment decision works, the investment rules play decisive roles in directing the network evolution. In our experiments, we will illustrate that applications of slightly different cost-benefit evaluation rules may end up with quite different features of the city system in the long run.

(2) Cost-Benefit Evaluation Rules

The investment decisions are taken by the central government, that controls the travel costs between the cities by improving the existing transportation links. Let us introduce the discrete time system. At the beginning of each period, the investment decision is supposed to be made. At each period, only one link with the largest value of the benefit-cost ratios is improved as far as the ratios exceed the (predetermined) reservation levels. Throughout the whole periods, the same decision rule is mechanically applied without paying any reference other than the values of benefit-cost ratios.

In the simulation experiments, we consider three kinds of cost-benefit evaluation rules. The rules are named as follows: 1) the *naive* rule (*caseA*), 2) the *intermediate* rule (*caseB*), and 3) the *sophisticated* rule (*caseC*), in the order of calculation complexity. The *naive* rule is the simplest one. In applying this rule, the government only calculates the aggregated change in the consumer surplus provided that OD trip demands and population patterns remain unchanged. The overall benefit by using the consumer surplus is simply calculated by applying the formula:

$$B^* = \sum_{i=1}^{n} \sum_{j \neq i}^{n} R_{ij}(d_{ij} - d'_{ij}), \tag{18}$$

where B^* is the *naive* measure of benefits gained by the improvement, R_{ij} is the current OD trip volume, d_{ij} is transportation cost between node i and j before the improvement is made, and $d'_{ij}$is transportation cost after the improvement. In the calculation with the *intermediate* rule, the changes of OD trip demands are taken into account provided that the demand functions are supposed to be unchanged. The *intermediate* measure of benefits B^{**} is approximated by

$$B^{**} = \sum_{i=1}^{n} \sum_{j \neq i}^{n} \frac{1}{2}(R_{ij} + R'_{ij})(d_{ij} - d'_{ij}). \tag{19}$$

The demand function is defined by eq.(14). In calculating the change in R_{ij}, the change of d_{ij} in eq.(14) is only considered, while regional output Y_i is supposed to be unchanged. In case of the *sophisticated* rule, the calculations are made by considering both the change in the OD trip patterns and the sifts in the demand curves. The *sophisticated* measure B^{***} is practically defined as the change in the equilibrium utility levels summed up over the whole population of the overall system, measured in monetary terms, which is driven by the network improvement:

$$B^{***} = (\overline{V}' - \overline{V})N, \tag{20}$$

where $\overline{V}'$ and $\overline{V}$ indicate the equilibrium utility levels after and before the link improvement respectively, and N is the total population of the whole system. The *sophisticated* rule reflects the full benefits of the network improvement.

(3) Adjustment Speed

As will be explained in **5.**, the initial conditions are highly decisive in regulating the subsequent evolution paths.

Once the city system starts to evolve from a certain initial condition, it becomes difficult to control spatial agglomeration process. The network improvements with cost-benefit evaluation rules are always taken to reinforce the ongoing agglomeration process. This is partly due to the assumption of our model that the city system can immediately adjust itself to the change in network structure. In reality, the city system can adjust itself only with time lags. If the system is staying at disequilibrium states, being far from the equilibrium state, the spatial agglomeration processes could be partly controlled by the network improvement. Thus, the adjustment speeds are another significant ingredients which may regulate the evolution processes with cost-benefit evaluation rules. The disequilibrium dynamics of the city system can be characterized by the following population dynamics[19)20)]:

$$s_{t+1}(i) = s_t(i) + \lambda \frac{(V_t(i) - \overline{V}_t)s_t(i)}{\overline{V}_t} \tag{21}$$

where $s_t(i)$ is the share of population of the i-th city to the total population at the beginning of period t, λ is the adaptation parameter reflecting the adjustment speed of convergence, $V_t(i)$ is the utility level of the i-th city at period t, and $\overline{V}_t = \sum_i s_t(i)V_t(i)$ is the average utility level of the whole system calculated by taking the average of the utility levels of all the cities weighted by the share of population. Population dynamics (21) satisfies the adding-up constraint. In fact, by summing up both sides of eq.(21), we see that $\sum_i s_{t+1}(i) = \sum_i s_t(i) + \lambda\{\sum_i V_t(i)s_t(i)/\overline{V}_t - \sum_i s_t(i)\} = 1$, if $\sum_i s_t(i) = 1$. Provided $\sum_i s_0(i) = 1$, there hold $\sum_i s_t(i) = 1$ for all the periods. The total population of the system is assumed to be constant N over the whole evolution period. This population dynamics implies that the population moves toward the locations with above-average utility levels and away from those with below-average.

5. COMPUTATIONAL SIMULATIONS

(1) Description of Simulations

The network of cities simulated is a simple grid system which lies on a flat ground. The network simulated consists of 5 x 5 = 25 cities. All links are assumed to have the same length and the same cost of improvement. The central government improves the existing transportation connections by introducing a higher-level transportation system. At one stage of the network evolution the government improves only one link which is selected according to the cost-benefit evaluation rule. The links which have been improved once cannot be improved further, which is assumed just for vehicles of comparison. By assuming so, the degree of the concentration can be simply compared with respect to the number of links having been constructed. This is, however, a restrictive assumption to explore the properties of evolution process of the network. If reimprovement of a single link is allowed, evolution patterns may end up with more concentrated networks, with fewer but highly improved links. The improvement costs are fully financed by the tax revenue within the respective periods. The government is assumed to leave no debt for the future.

The cases where the system can instantly adjust itself to the network improvement are taken up as the benchmark case. The network evolution is simulated as follows: 1) given the initial populations, the system is brought into equilibrium before any link improvement is made; 2) the urban economic submodel is simulated to calculate the benefit for all of the unimproved links; 3) if link improvement is justified, the link chosen by the cost-benefit evaluation rules is improved by decreasing the transportation cost on that link from its initial value of $d_{ij} = 1.0$ to $d'_{ij} = 0.7$; 4) then, evolution proceeds to the next period; 5) the system is brought into the new equilibrium by using the general equilibrium model starting from the equilibrium state at the end of the previous period. This process is repeated until no network improvement is justified by the cost-benefit evaluation rules. The main technical assumptions for simulations are as follows: The population is allowed to migrate throughout the evolution process, and the cities whose population become zero once (the cities that die), are not allowed to reborn. Furthermore they are not included in the calculations for utility equilibrium. Other important factors in designing the simulation experiments are the choice of the parameters α, ξ, γ, and the initial distribution pattern of city populations. In our simulations, the parameter values are set to: $\alpha = 0.7$, $\xi = 0.6$, $\gamma = 0.5$, and the tax value is taken as $\tau = 0.044$. Given these parameter values, the production technology exhibits the property of constant returns to scale. The interactability across the whole network forms the external economies of production in cities. At the initial stage, given the initial network pattern, the city system is assumed to reach its initial equilibrium state.

(2) Multiplicity of Equilibrium

The equilibrium states at each point in time as well as evolution processes of the city system depend highly upon the

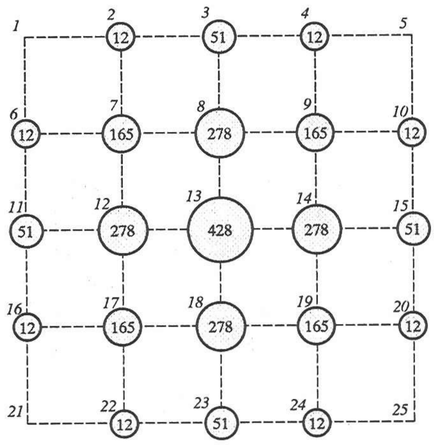


Figure 1.a Initial Equilibrium (example 1)

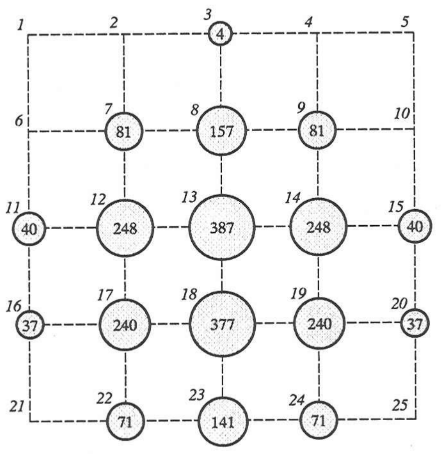
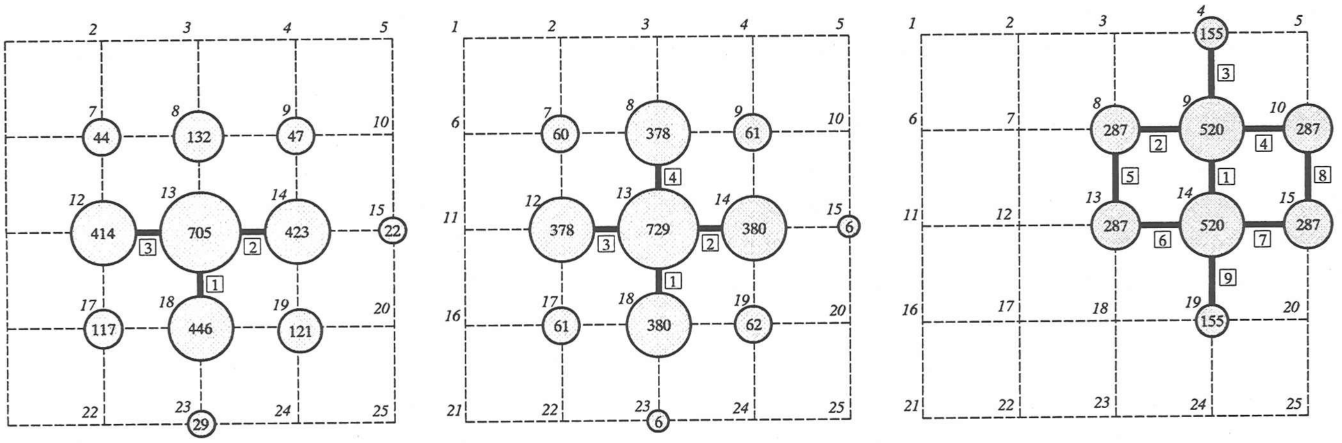


Figure 1.b Initial Equilibrium (example 2)



(a)Case A (b)Case B (c)Case C

Figure 2 Final Equilibrium After Network Evolution

initial equilibrium of population distribution. In order to observe the effects of the initial equilibrium states upon the network evolution process, different simulations with different initial equilibrium states have been conducted. In order to obtain the initial equilibrium states, given different hypothetical patterns of population distribution which were artificially generated, the city systems were brought into the initial equilibrium states. The system can be characterized by the multiplicity of the initial equilibrium states. **Figures 1.a** and **1.b** illustrate examples of initial equilibrium among possible equilibrium states. **Figure 1.a** exhibits an equilibrium pattern symmetric both along the vertical and horizontal axes passing through the central node of the network. This equilibrium was obtained started from an initial hypothetical pattern of evenly distributed population. On the other hand, **Figure 1.b** illustrates another equilibrium pattern showing asymmetric distribution of population, which was obtained from a skewed initial distribution. Thus, we know that at the beginning of period 0 before network evolution starts, there exist many initial equilibrium states. The selection of different initial equilibrium states may end up with the entirely different final city systems through evolution processes, and is crucial in regulating evolution processes. In what follows, simulation experiments based upon the symmetric initial equilibrium state will be investigated.

(3) Results

Let us first investigate simulation results for the benchmark case. The benchmark case is the one in which the

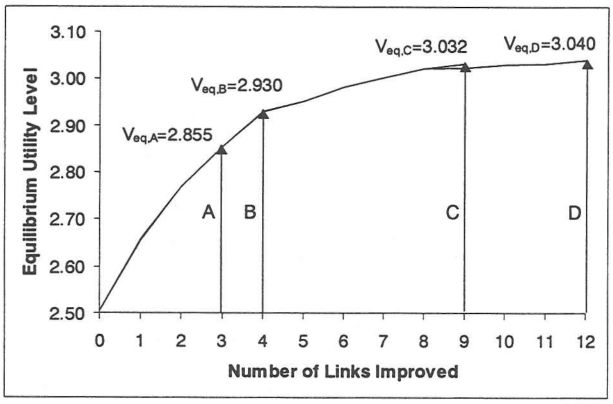


Figure 3 Network Evolution Patterns(Benchmark Case)

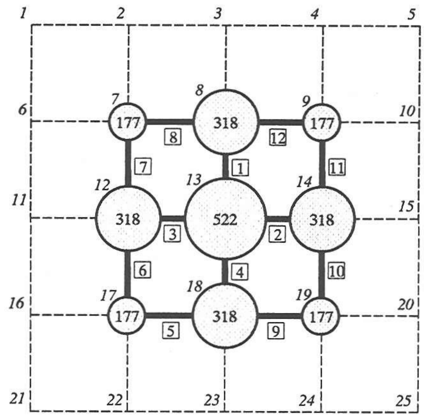


Figure 4 Final Equilibrium (case D)

population in the system moves freely without any friction, so that the system comes to full equilibrium at the end of each period. The simulations for the benchmark case show that there exist a number of different evolution patterns due to the selection of the cost-benefit evaluation rules. **Figures 2.(a)**, **2.(b)**, and **2.(c)** illustrate the final network patterns when the investments are terminated with the respective cost-benefit rules. In these figures, the numbers in the small squares indicate the order of link improvement, whereas the size of the circles and the numbers inside them correspond to the size of the population in that city. Node points without any circle indicate cities with zero population. Doted lines indicate the initial connection between cities, whereas the solid lines show the links that have been improved according to cost-benefit evaluation rules. **Figures 2.(a)**, **2.(b)**, and **2.(c)** refer to the cases where the *naive*, *intermediate*, and *sophisticated* rules are applied, respectively. Cases A, B, and C also refer to the *naive*, *intermediate*, and *sophisticated* benefit calculations, respectively. In **Figure 2.(a)**, we see that there is only 3 links improved when the *naive* rule is applied, however the number of link improvements becomes 4 (**Figure 2.(b)**), and 9 (**Figure 2.(c)**) for the *intermediate* and *sophisticated* rules, respectively. **Figure 3** shows the relationships between the equilibrium utility levels attained by the respective rules and the total number of links improved for each case. First thing to note is that the amount of benefit calculated shows a great difference with respect to the rule utilized. In general, as the rule applied becomes more complicated, the benefit calculated increases and as a result more number of links can be improved. For cases A, B, and C the equilibrium utility levels follow the similar, but slightly different paths (though they look to follow the same paths in **Figure 3**). From **Figure 3** we see that the different cost-benefit evaluation rules may lead to large difference in the equilibrium utility levels in the long run. As far as our simulations are concerned, the application of coarse and *naive* cost-benefit evaluation rules may end up with over-concentrated networks which attain lower efficiency than the case where *sophisticated* rules are applied. Thus, we see that more sophisticated and precise evaluation is required to attain more decentralized and efficient network. Another important observation that can be made from **Figure 2.(c)** is that the evolution starts from a link which is different than any of the central links of the network.

In order to see the effect of the initial link formation upon the subsequent network evolution, an independent simulation (case D) is also made provided that one of the central links of the network, link 8-13, is initially improved by some political initiative. The final network structure for this case is given in **Figure 4**. Comparing this figure to **Figure 2.(c)**, we see that the final patterns of the network and the population distributions are quite different from each other. The comparison of the two cases shows how drastically the resulting network can change depending on the selection of the initial link. Once the selection of the initial link is made, the subsequent link improvements are very conditional to that link. As it can be observed from **Figure 3**, when the first link improvement is chosen by political initiatives, the equilibrium utility levels achieved are higher than the case where the first link is decided by the *sophisticated* rule. In the former case, the final network structure becomes larger than the latter case. These findings imply that the initial link should not be solely designed by the cost-benefit evaluation rule; rather the spatial expansion capability of the network should also be taken into account in selecting the first link to be improved. Considering that

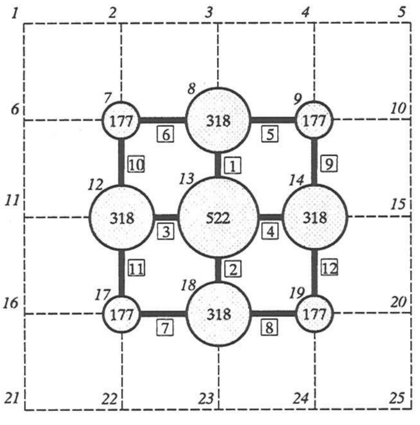


Figure 5 Final Equilibrium (case C')

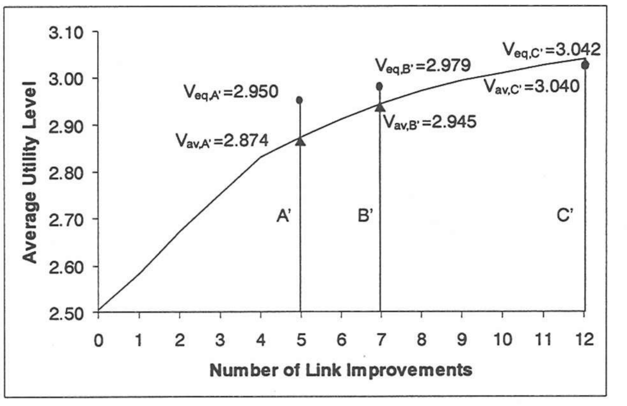


Figure 6 Network Evolution Patterns(Reference Case)

the initial equilibrium utility of the system before link improvements was 2.505, the amount of increase in case D is about 1.5%, 25.9% and 52.9% higher than in cases C, B and A, respectively.

For comparison, simulations are also made with the same decision rules provided that the systems evolve with time lags following eq.(21) without reaching full equilibrium at the end of the link improvement. For this case, $\lambda = 10.0$ is assumed and the population is moved at five steps with the given migration speed, rather than moving it at once with a higher migration speed. Here, again, cases A', B', and C' correspond to the evolution patterns applying, *naive*, *intermediate*, and *sophisticated* benefit rules, respectively. **Figure 5** illustrate the final equilibrium in Case C'. The network equilibrium in case C' is the same as in case D, while the sequences of link improvement are different. **Figure 6** shows the average utility levels when the newtork evolution is terminated and the equilibrium utility levels achieved in the long run. First of all, it can easily be observed that initial link improvement is a central link for all of the cases. Second is that the total number of link improvements is higher than the case with full equilibrium. This is, of course, due to the higher benefit values achieved. If we compare **Figure 6** with **Figure 3**, we see that the equilibrium utility levels in case of C' follow a flatter path, until the very final link improvement is over. The reason for this is that in the case with time lags for adjustment the system is not necessarily brought into equilibrium at the end of each period. After network improvement is terminated at some certain point, the utility levels are still moving toward a long-term equilibrium one. The average and the long-term utility levels are indicated with V_{av} and V_{eq} in **Figure 6**. The long-term equilibrium utilities, V_{eq}, are higher than the average utility levels, V_{av}, in cases A' and B' and lower in case C'. Comparing the long-term equilibrium levels of cases A', B', and C' with each other, we see that the increase in the equilibrium utility level (regarding that the initial equilibrium utility was 2.505) achieved in case C' is about 13.0% and 20.1% higher than in cases B' and A', respectively. With the existing results we can say that the final network structures are very sensitive to the values of adjustment speed. This finding implies that more careful cost-benefit evaluations are needed to decide the sequence of the network link improvements, if the decision maker wishes to contemplate on the effects of adjustment speed on the results of cost-benefit analysis.

6. CONCLUSION

The cost-benefit evaluation rule guarantees the government to make the local optimal decisions, given the history of the network evolution. The successions of the local optimal improvement need not to reach the global optimal state. This is especially true if the city system is inherently characterized by the multiplicity of the equilibria. Though only limited number of simulation experiments are dealt with, we have succeeded to illustrate that the simple succession of the cost-benefit evaluation rules may end up with highly centralized systems having low efficiency. As far as our simulation experiments are concerned, this is especially clear when decisions are made by coarse and naive cost-benefit calculation. It must be noted, however, that it is dangerous to derive the general conclusion based upon the limited number of simulated results. The evolution possibility with cost-benefit evaluation rules still needs further scrutiny from various angles.

The simulation model presented in this paper still remains at a prototype level. The model should be improved to make more careful investigation. Among others, the following revisions should be made: 1) rebirth of cities should be considered (policy initiatives may lead to the formation of new city), 2) simultaneous improvement of multiple links should be discussed, 3) multiple quality ranks for link improvement must be considered, 4) the factors neglected in the model, e.g. knowledge, capital, and trade should be considered. Especially, growth modeling is the most important direction of further development. The issues around lock-in effects in the dynamic setting remain unsolved. Although awaiting further development and sophistication, our simulation experiments are encouraging in that they seem to capture the essential mechanism controlling the evolution process of the city systems with cost-benefit evaluation rules.

References

1) Kobayashi, K., Batten, D.F., and Andersson, Å.E.: The sequential location of knowledge-oriented firms over time and space, *Paper of Regional Science*, Vol. 70, pp. 381-397, 1991.
2) Batten, D.F., Kobayashi, K., and Andersson, Å.E.: Knowledge, nodes and networks: an analytical perspective, in: Andersson, Å.E. *et al.*(eds.), *Knowledge and Industrial Organization*, Springer Verlag, Berlin, 1989.
3) Fujita, M.: Monopolistic competition and urban systems, *European Economic Review*, 37: 308-315, 1993.
4) Arthur, B.: *Increasing Returns and Path Dependence in the Economy*, Ann Arbor: The University of Michigan Press, 1994.
5) Fujita, M, Krugman, P., and Mori, T.: On the evolution of hierarchical urban systems, Discussion Paper 419, Institute of Economic Research, Kyoto University, 1995.
6) Matsuyama, K., Complementarities and cumulative process in models of monopolistic competition, *Journal of Economic Literature*, 33: 701-729, 1995.
7) Kanemoto, Y. and Mera, K.: General equilibrium analysis of the benefits of large transportation improvements, *Regional Science and Urban Economics*, Vol. 15, pp. 343-363, 1985.
8) Sasaki, K.: Trade and migration in a two-city model of transportation investments, *Annals of Regional Science*, Vol. 26, pp. 305-317, 1992.
9) Henderson, J. V.: *Economic Theory and The Cities*, Academic Press, 1985.
10) Abdel-Rahman, H. M.: Agglomeration economies, types, and sizes of cities, *Journal of Urban Economics*, Vol. 27, pp. 25-45, 1990.
11) Krugman P.: Increasing returns and economic geography, *Journal of Political Economy*, Vol. 99, pp. 483-499, 1991.
12) McKibbin W. J. and Sachs, J. D.: *Global Linkages: Macroeconomic Interdependence and Cooperation in the World Economy*, Brookings Institution, 1991.
13) Shoven, J. B. and Whalley, J.:*Applying General Equilibrium*, Cambridge University Press, 1992.
14) Mun, S.-I.: Transport network and system of cities, *Journal of Urban Economics*, Vol. 42, pp. 205-221, 1997.
15) Kobayashi, K. and Okumura, M.: The growth of city systems with high-speed railway systems. *Annals of Regional Science*, Vol. 31, pp. 39-56, 1997.
16) Marshall, A.: *Principle of Economics*, 8th edition, London: Macmillan, 1920.
17) Romer, P. M.: Increasing returns and long-run growth, *Journal of Political Economy*, 94: 1002-1037, 1986.
18) Lucas, R. E.: On the mechanics of economic development, *Journal of Monetary Economics*, 22: 3-22, 1988.
19) Maynard Smith, J.: *Evolution and the Theory of Games*, Cambridge University Press, 1982
20) Hofbauer, J. and Sigmund, K.: *The Theory of Evolution and Dynamical Systems*, Cambridge University Press, 1988.

費用ー便益評価ルールに基づくネットワークの進化過程

メフメット・アリ・ツンチェル，栗野盛光，小林潔司

本研究では交通ネットワーク形成による都市システムの進化過程に関するシミュレーション実験を試みたものである．政府がネットワークの逐次的な形成過程を費用便益分析で決定した場合，都市システムが大都市を中心とする都市システムに進化するとともに，地理的な条件だけでなくネットワークの投資順位が都市システムの構造形成に本質的な役割を果たすことを示している．

NETWORK EVOLUTION WITH COST-BENEFIT EVALUATION RULES

By Mehmet Ali TUNCER, Morimitsu KURINO, and Kiyoshi KOBAYASHI

This paper attempts to provide with some simulation experiments for the policy driven development by revealing how city systems evolve throught time in response to policy initiatives for network formation. By assuming that the government applies cost-benefit evaluation rules to improve railway network one by one, the paper illustrates that city systems will evolve in such a manner that population will indeed cluster in some dominant locations, and that they depend both on the geographical conditions and historical order of network improvement.