TECHNOLOGICAL SUBSTITUTION BETWEEN TELECOMMUNICATIONS AND TRANSPORTATION IN PRODUCTION - A THEORETICAL PERSPECTIVE -

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1. INTRODUCTION

This paper falls within that category of planning thought in which the stocks of knowledge are regarded as input variables in production. Far from being used up in the process of production, we consider that knowledge is made available to firms by way of exchange processes on a spatial network. The nodes in this network take discrete forms of human settlements such as towns, cities, or metropolitan regions; the links between nodes facilitate knowledge acquisition and knowledge expansion. Firms may choose to undertake their own R & D activities to expand their own stocks of knowledge, but eventually such stocks become available to other firms at other nodes on the spatial network.

This paper addresses to the following three points. First, the paper points out that there should be interactions among the stocks of knowledge and its distribution over space in the form of knowledge production units located within different nodes of a discrete network. The spread of advanced telecommunications has resulted in an increased availability to knowledge, particularly in the form of uncomplicated and routinized knowledge. The fundamental importance for the role of telecommunications in production is the fact that information and messages to a large extent can be subdivided into small pieces and be stored with some simplicity for a longer or shorter time.

Second, the paper addresses to the fact that people have to be moved in individual units so as to acquire knowledge and be supplied with a number of services in movement. The advances in transportation technology have made it possible to overcome the friction of distances to a great extent. As a result, the distance has become a by far weaker constraint on transshipment of messages and has acquired increasingly smaller importance in the transportation of goods. However, the distance friction in transportation has been and will still be a considerable constraint on movement of people.

Finally, the paper focuses on the fact that a fundamental feature of the modern firms is characterized by a high frequency of communications among persons and organizations. If standardized and routinized knowledge is exchanged, contacts by transportation can be substituted by telecommunications. However, when knowledge to be exchanged has a high degree of indivisibility, face-to-face contacts by transportation are inevitable. It is possible for the production of goods to decentralize, because of decreasing costs of goods transportation and increasing possibilities of substitution of human work for the inputs of robot power and the use of computerized production control. However, industries which are strongly dependent upon highly intensified R & D activities and which require direct communications between people, such as negotiations and the transmission of new knowledge, tend to concentrate in metropolitan areas.

Our emphasis will be on micro behavioral analysis of technological substitution between telecommunications and transportation in knowledge production and the consequences of regional division of knowledge labour force. Three particular strands of analytical thoughts have important parts in our approach. First, the role of knowledge-handling occupations is portrayed as a fundamental one in the structural representation of each node's labour supply and in the process of acquiring/exchanging knowledge. Second, the spatial network is modeled as a discrete network with a view to emphasizing the degree of decomposability of economic systems and the node-to-node nature of exchange processes. Third, two classes of production functions are drawn upon, that is, a knowledge production function and a real production function. They play an essential role in analyzing regional division of knowledge production.

In our modeling, the knowledge stocks are regarded as public goods, available to various firms and organizations by way of a spatial network. As an input to the production process, knowledge takes the form of a reusable resource. A production function for the knowledge level of a nodal firm is derived in terms of the sizes of its knowledge-handling labour force and the firm's accessibility to the complete stocks of knowledge in all nodes, by means of networks of telecommunications and transportation. The micro economic behavior of modern firms which are highly dependent upon the intensive communications with other firms and organizations is analyzed. Based upon the above obtained theoretical perspective, the paper concludes by assessing its analytical implications in R & D oriented regional policy making.

2. ECONOMIC ANALYSIS OF KNOWLEDGE PRODUCTION

2.1 Knowledge and the Production Function

Economic theory currently embraces a lengthy tradition wherein knowledge stocks and the associated flow variable, R & D activity, are regarded as the factors exogenous to the production function. Given the active policy debate among the advanced nations on the role of R & D in the economic system, it seems more fruitful to examine the question of how knowledge-based inputs interact with conventional inputs in the production process. Some progress has been made in this direction by subdividing investment resources into those which are knowledge-based (R & D) and those which are material-based (tangible capital)(1).

Recently, Andersson and Andersson et al. have adopted both occupational and educational decompositions to demonstrate that labour should not be treated as a homogeneous production factor in modeling of regional economic growth (2)(3). An occupational classification of labour inputs in the production function parallels the disaggregation of interindustry inputs found in input-output formulations of the production functions. One of the most fundamental aspects in production is that knowledge acquisition and diffusion largely proceed independently of specific advances in applied technical knowledge (or process R & D). Most stocks of knowledge have a public goods character, since they contribute as a factor input without being used up by the production process. Although a few firms engage in their own private R & D activity, eventually this knowledge diffuses more widely so that many other firms have access to it (1).

To cater for this public goods character of knowledge, we shall define each nodal firm's production function by assuming that the production of knowledge is strongly separable from the conventional production technology. Thus we have

$$Q_i = g(D_i,G)f(K_i,L_i) \ , \qquad (1)$$

where Q_i is the output of firm i, K_i the amount of capital of firm i, L_i the amount of non-knowledge-handling labour, D_i the capacity of information, and $G=(G_1,\text{---},G_n)$ an array of the amounts of knowledge-handling labour in nodes. $g(D_i,G)$ denotes the knowledge production function and $f(K_i,L_i)$ denotes the conventional production technology. Our assumption of strong separability implies that the production of knowledge derived from process R & D shifts the frontier of the real production function f upwards with respect to the frontier of the conventional production function h (4). This is akin to the notion of Hicks neutrality.

Assuming that all firms (nodes) are price-takers, competing only by way of differences in process R & D within an otherwise perfectly competitive marketplace, the optimization problem of the firm is to choose the best levels of K_i,L_i,D_i and G_i so as to

$$\text{Max} \ \{ p_i g(D_i,G)f(K_i,L_i)-\omega_i K_i-\theta_i L_i-\eta D_i-\xi G_i\} \ , \qquad (2)$$

where p_i is the f.o.b price of the firm's product, ω_i the rent on capital, θ_i the wage rate of non-knowledge handling labour, η the rent of information systems, and ξ the wage rate of knowledge workers.

2.2 Accessibility to Knowledge

Knowledge is made available to firms by way of exchange processes on a spatial network of knowledge. The term "spatial network" is used to denote a set of nodes together with the links connecting the nodes (See Fig. 1). The nodes in a knowledge network take the discrete form of human settlements such as towns, cities, or metropolitan regions. These can be characterized by their constellation of knowledge production capacities and pertinent activities, their knowledge infrastructure such as universities, research centers, etc., their stocks of knowledge and human capital, and their local networks of knowledge. The links between nodes facilitate flows which comprise the displacement of messages, information, and knowledge by making use of the dual network structure, transportation and telecommunication networks (4).

There should be interactions among the stocks of knowledge and their distribution over space in the form of knowledge production units located within different nodes of the knowledge network. A fundamental feature of knowledge production firms is the high frequency of communications among persons. If standardized information is exchanged, contacts can be substituted by telecommunications. However, when the knowledge to be exchanged has a high degree of indivisibility, face-to-face interacts requiring transportation are inevitable.

Description of interdependencies in a spatial public good analysis is most conveniently handled with an accessibility representation. Accessibility measures can be regarded as the spatial counterparts of discounting public goods. Thus they represent the distribution of public goods in a simple way that imposes a very clear structure upon the relationship between activities and their environment. Accessibility to knowledge is determined by various

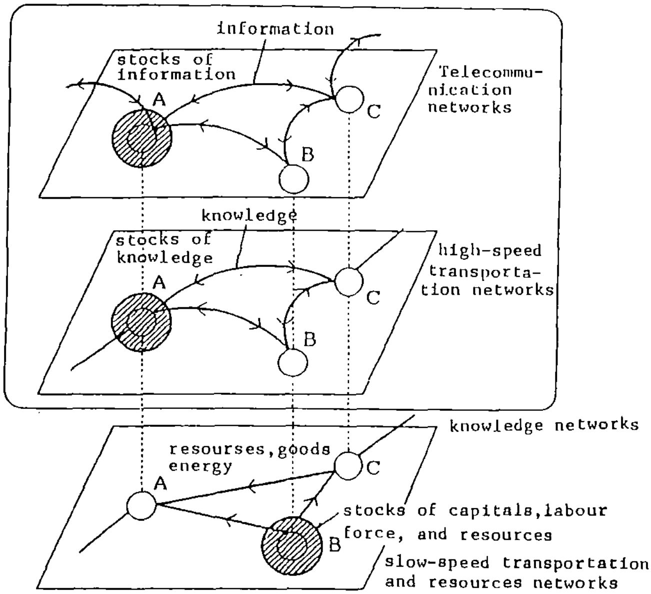


Fig. 1 Knowledge Network

frictional effects arising from geographical, social, political, educational or psychological "distances" between knowledge workers or knowledge centers.

Let us introduce two measures of accessibility to knowledge; viz. telecommunication accessibility and face-to-face accessibility. Telecommunication accessibility measure, AC_{1i}, describes the system-wide availability of knowledge of node i across the computer and telecommunication networks, which is defined as

$$AC_{1i} = \sum_j \sigma_1 f_{ij1} G_j^{\gamma}, \tag{3}$$

where σ_1, γ_1 are parameters, $f_{ij1} = \exp(-\beta d_{ij1})$, where β denotes the distance friction for knowledge exchange across the telecommunication networks, d_{ij1} the inter-nodal distance between nodes i and j, and G_j the amount of knowledge handling labour in node j. The face-to-face accessibility of node i to all other nodes, including its own public R & D units (e.g. universities) is formulated as

$$AC_{2i} = \sum_j (\sigma_2 f_{ij2} W_j^{\gamma_2} + \sigma_3 f_{ij2} G_j^{\gamma_3}), \tag{4}$$

where σ_2, σ_3, γ_2 and γ_3, are parameters, W_j the scale of node j's public R & D units and f_{ij2} the distance friction for knowledge exchange on the transportation networks. While the distance plays a role of decreasing importance in the exchange processes of data, knowledge and information on the telecommunication networks, the distance friction on the transportation networks now and in the future will be considerable in movement of people(4). Thus, it may well be justified to assume that $f_{ij1} << f_{ij2}$.

Accessibility measures such as (3) and (4) determine each node's knowledge exchange potential. Therefore, the AC_{i1}- and AC_{i2}-values are considered appropriate additional arguments in the knowledge production function, $g(D_i,G)$, such that

$$g(D_i,G) = g(D_i,G_i,AC_{1i},AC_{2i}) \ . \tag{5}$$

The above formulation will be elaborated upon in the next section. Each firm chooses the optimal level of output and the required mix of inputs so as to maximize equation (2), given the distribution of knowledge workers in other nodes, viz. G_1, $G_2, \ldots\ldots G_{i-1}$, $G_{i+1}, \ldots G_n$ and their own node's scale of public R & D. Here we assume that the spatial allocation of public R & D (W_1, $W_2, \ldots\ldots$, $W_i, \ldots\ldots W_n$) is provided by public sectors.

2.3 The Optimal R & D Policy

Rewriting equation (2) by using equation (1),(4) and (5) leads to the firm's profit-maximizing problem formulated as

$$\text{Max} \ \{ p_i g(D_i,G_i,AC_{1i},AC_{2i}) f(K_i,L_i) - \omega_i K_i - \theta_i L_i - \eta D_i - \xi G_i \} \ , \tag{6}$$

where the values of ω_i and θ_i are specified for each node i. Here, η and ξ are assumed to be uniform across the whole network of firms. This distinction emphasizes that the wage levels of knowledge workers and the rent levels of information systems are assumed to be uniform rather than location-specific.

A typical form taken by the production function f is the Cobb-Douglas function:

$$f(K_i,L_i) = aK_i{}^b L_i{}^c \ , \tag{7}$$

where a, b and c are parameters, and we assume that b+c<1. If we assume for the moment that the size of firm i's knowledge workforce is fixed at $\hat{G}_i$ and that the capacity of information systems at $\hat{D}_i$. Given the output level, $\bar{Q}_i$, the above optimization problem reduces to the following cost-minimization problem:

$$\text{Min}_{K_i,L_i} \ \{ \omega_i K_i + \theta_i L_i + \eta \hat{D}_i + \xi \hat{G}_i \}$$

subject to

$$\bar{Q}_i = g(\hat{D}_i,\hat{G}_i,AC_{1i},AC_{2i}) f(K_i,L_i) \ . \tag{8}$$

Then the cost function becomes

$$C(\bar{Q}_i;\hat{D}_i,\hat{G}_i) = \{g(\hat{D}_i,\hat{G}_i,AC_{1i},AC_{2i})\}^{-1/s} T_i \bar{Q}_i{}^{1/s} - \eta\hat{D}_i - \xi\hat{G}_i , \tag{9}$$

where s = b + c and T_i is a constant given by

$$T_i = a^{-1/s}\{(b/c)^{c/s}+(b/c)^{-b/s}\}\omega_i^{b/s}\theta_i^{c/s} \quad . \qquad (10)$$

Now allow $\bar{Q}_i$ to vary with D_i and G_i fixed at $\hat{D}_i$ and $\hat{G}_i$. Our profit function becomes

$$\text{Max}_{\,Q_i} \{p_i Q_i - C(Q_i;\hat{D}_i,\hat{G}_i)\} \quad . \qquad (11)$$

Assuming decreasing returns to scale, i.e. $b + c \leq 1$, there exists an optimal solution to (11) for arbitrary values of $\hat{G}_i$ and $\hat{D}_i$. Let Q^* be the optimal solution. Substituting Q_i^* into (11), we obtain the optimal profit function:

$$\Pi(\hat{D}_i,\hat{G}) = \Psi_i\{g(\hat{D}_i,\hat{G}_i,AC_{1i},AC_{2i})\}^{\rho} - \eta\hat{D}_i - \xi\hat{G}_i \quad , \qquad (12)$$

where ρ and Ψ_i are constants given by

$$\rho = 1/(1-s) \quad ,$$

$$\Psi_i = T_i^{-\rho s}\{p_i(p_i s)^{\rho s} - (p_i s)^{\rho}\} \quad .$$

According to Hotelling's lemma (5), by differentiating the profit function with respect to the factor prices, we obtain the factor demand functions:

$$K_i = \delta(b\theta_i/c\omega_i)^{c/s}\{g(\hat{D}_i,\hat{G}_i,AC_{1i},AC_{2i})\} \quad ,$$

$$L_i = \delta(b\theta_i/c\omega_i)^{-b/s}\{g(\hat{D}_i,\hat{G}_i,AC_{1i},AC_{2i})\} \quad , \qquad (13)$$

where

$$\delta = a^{-1/s}(p_i s/T_i)^{\rho}.$$

Now let the D_i and G_i be treated as variables. Using (12), eq.(11) becomes

$$\text{Max}_{\,D_i,G_i} \{\Psi_i[g(D_i,G_i,AC_{1i},AC_{2i})]^{\rho} - \eta D_i - \xi G_i\} \quad . \qquad (14)$$

The first-order optimality condition of eq. (14) is

$$\eta = \rho\Psi_i[g(D_i,G_i,AC_{1i},AC_{2i})]^{\rho-1}\Omega_{Di}(D_i,G) \quad ,$$

$$\xi = \rho\Psi_i[g(D_i,G_i,AC_{1i},AC_{2i})]^{\rho-1}\Omega_{Gi}(D_i,G) \quad , \qquad (15)$$

where $\Omega_{Di}(D_i,G) = \partial g(D_i,G)/\partial D_i$ and $\Omega_{Gi}(D_i,G) = \partial g(D_i,G)/\partial G_i$. The second-order optimality conditions are assumed to be satisfied. Rearranging (15) gives the following factor demand equations for knowledge workers and information systems in node i, respectively:

$$D_i^* = \Lambda_{Di}(D_i^*,G^*;\eta,\xi) \quad ,$$

$$G_i^* = \Lambda_{Gi}(D_i^*,G^*;\eta,\xi) \quad . \qquad (16)$$

The optimal value D_i^* and G_i^* can be obtained by solving equation (16). By substituting this back into equation (13), we may also obtain the optimal levels of the conventional factor inputs, namely K_i^* and L_i^*.

2.4 Nash Equilibrium

So far we have restricted our discussion to a single firm (in node i) without considering the decisions or reactions of others. It may well be the case that R & D decisions of each firm will influence the corresponding decisions of other firms. Such interactions over knowledge networks may occur in a non-cooperative manner, in which case the resulting spatial equilibrium will correspond to a Nash equilibrium (6). The criterion to generate the equilibrium solution is that the optimality conditions for knowledge production levels should be satisfied simultaneously in every location. This can be induced from the description of a possible pattern of reactions of agents, which choose their optimal levels of outputs in a non-cooperative way. Thus, our equilibrium can be given by a solution of the following equations:

$$D_i^* = \Lambda_{D_i}(D_i^*, G^*; \eta, \xi), \quad (i=1,---,n) \quad ,$$

$$G_i^* = \Lambda_{G_i}(D_i^*, G^*; \eta, \xi), \quad (i=1,---,n) \quad , \tag{17}$$

where $G^* = (G_1^*, \ldots\ldots, G_n^*)$, $D^* = (D_1^*, \ldots\ldots, G_n^*)$ and may be formulated as a fixed point problem.

3. REGIONAL DIVISION OF KNOWLEDGE LABOUR FORCE

3.1 Specification of Knowledge Production Function

Different specification of knowledge production functions may produce different types of spatial equilibrium models. To illustrate how knowledge production technology determines regional divisions of knowledge labour force, we shall confine our present analysis to a simple model where knowledge production technology can be described as a Cobb-Douglas production function. The assumption of Cobb-Douglas type of technology is so restrictive in order to investigate technological substitution between telecommunications and transportation in knowledge production (7). It turns out, however, that this seemingly trivial case provides pedagogical insights of practical significance. More realistic and sophisticated models may be developed in due course.

Following on from (5), we shall assume that the knowledge production function takes the Cobb-Douglas type of production functions:

$$g(D_i, G) = D_i^{\alpha_1} G_i^{\alpha_2} AC_{1i}^{\alpha_3} AC_{2i}^{\alpha_4}, \tag{18}$$

where α_1, α_2, α_3, and α_4 are parameters and AC_{1i} and AC_{2i} the telecommunication and face-to-face accessibility measures, respectively. The logic of equations (18) is that the frequency of knowledge exchanges among knowledge workers depends partly on firm's knowledge resources and partly on their accessibility to knowledge stocks both on telecommunication and transportation networks. Knowledge worker's level of interactivity may be measured in terms of accessibility measures which may approximate the availability of knowledge over the whole network. The values of parameters in knowledge production function may differ across the types of industries depending upon their technology of knowledge production.

According to (14), each firm's level of R & D is chosen to maximize its own profit function, i.e.

$$\text{Max}_{D_i,\ G_i}\ \{\ \Psi_i D_i^{\phi_1} G_i^{\phi_2} AC_{1i}^{\phi_3} AC_{2i}^{\phi_4} - \eta D_i - \xi G_i\ \}\ , \tag{19}$$

where $\phi_k = \rho\alpha_k$ (k=1,---,4). Assume the decreasing return technology in knowledge production, i.e. $\phi_1 + \phi_2 < 1$.

Given the decisions of the firms other than the i-th, let us maximize the i-th firm's optimal profit function (19) with respect to D_i and G_i. Let us here assume that firms do not take into account the indirect effects of their decisions on the increase of knowledge accessibility in choosing their optimal levels of knowledge inputs, i.e. $\partial AC_{1i}/\partial G_i = 0$ and $\partial AC_{2i}/\partial G_i = 0$. Then the first-order optimality condition for (19) is given by

$$D_i = \{(\Psi_i/\eta)\phi_1 G_i^{\phi_2} AC_{1i}^{\phi_3} AC_{2i}^{\phi_4}\}^{1/(1-\phi_1)}\ , \tag{20}$$

$$G_i = \{(\Psi_i/\eta)\phi_2 D_i^{\phi_1} AC_{1i}^{\phi_3} AC_{2i}^{\phi_4}\}^{1/(1-\phi_2)}\ . \tag{21}$$

Substituting eq. (20) into eq. (21), we get the fixed point problem:

$$G_i = J_i\ AC_{1i}^{\lambda_1} AC_{2i}^{\lambda_2}, \tag{22}$$

where $J_i=(\phi_1/\xi)^{\kappa_1}(\phi_2/\eta)^{\kappa_2}\ \Psi_i^{\kappa_3}$, $\kappa_1 = \phi_1/(1-\phi_1-\phi_2)$, $\kappa_2 =(1-\phi_1)/(1-\phi_1-\phi_2)$, $\kappa_3 = 1/(1-\phi_1-\phi_2)$, $\lambda_1 =\phi_3/(1-\phi_1-\phi_2)$ and $\lambda_2 = \phi_4/(1-\phi_1-\phi_2)$. Our spatial equilibrium model is therefore specified as

$$D_i = F_i(G)\ ,(i=1,---,n)\ , \tag{23}$$

$$G_i = H_i(G)\ ,(i=1,---,n)\ , \tag{24}$$

where F_i and H_i represent the RHS of eqs. (20) and (22). The spatial equilibrium of knowledge production can be given by a solution of nonlinear equations (23) and (24). Naturally, the choice of different forms of knowledge production function (19) would lead to different spatial equilibrium models.

3.2 The Existence of Fixed Points

The strong nonlinearity behind the spatial equilibrium conditions (24) may cause a great deal of complexity in the qualitative properties of regional divisions of knowledge labour force. It is not so easy to find the spatial equilibrium, since equilibrium conditions involve fixed point problem. The right hand side of eq. (24) is defined on the set C, $C = (0,\infty]^n$, which is not clearly compact. Thus the ordinary fixed point theorem cannot be utilized to ascertain whether there exist fixed points in (24). We must therefore derive the necessary conditions to guarantee the existence of such fixed points.

Assume that the wage rate of knowledge workers is endogenously determined in the labour market. For the moment, let us also assume that there exists a fixed point in (24) and denote the corresponding spatial equilibrium by $G_i^*(\xi)$, (i=1,.....,n). Let $\bar{G}$ be the total size of the knowledge workforce. Now assume that there exists an equilibrium wage ξ^* which satisfies

$$\bar{G} = \sum_i G_i^*(\xi^*)\ , \tag{25}$$

and let $J_i^*=J_i(\xi^*)$. Then for an equilibrium state (G^*,ξ^*), the following holds:

$$G_i = J_i^* AC_{1i}^{\lambda_1} AC_{2i}^{\lambda_2} \quad . \tag{26}$$

By summing up both sides of (28) with respect to i, we get

$$\begin{aligned}\bar{G} &= \sum_i G_i^*(\xi^*) \\ &= \sum_i J_i^* AC_{1i}^{\lambda 1} AC_{2i}^{\lambda 2} \quad .\end{aligned} \tag{27}$$

Then G_i^* satisfy the following equations:

$$G_i = \frac{\bar{G}\, J_i AC_{1i}^{\lambda_1} AC_{2i}^{\lambda_2}}{\sum_k J_k AC_{1k}^{\lambda_1} AC_{2k}^{\lambda_2}}, \quad (i=1,---,n) \; . \tag{28}$$

On the contrary, let us assume that the value of ξ in eq. (28) is fixed at a certain value. Obviously, eq. (28) is a continuous map defined on the compact set $R = \{G_j : \Sigma_j G_j = \bar{G}\}$. According to Brouwer's fixed point theorem (7), there exist fixed points in equation (28). Now define a parameter ξ and denote the spatial equilibrium (fixed point) as a function of this parameter: $G_i(\xi)$. If there exists a ξ^* which satisfies eq. (27), it is guaranteed that $G_i(\xi^*)$ satisfies eq. (26). Thus, the condition that there exist ξ^* satisfying eq. (27) for a given $\bar{G}$ is necessary for the existence of the equilibrium wage satisfying (25).

It is clear to ascertain whether a fixed point exists in (26), since J_i is a function of a single variable ξ. Where the value of J_i happens to be uniform over the whole network, our spatial model reduces to the following equations:

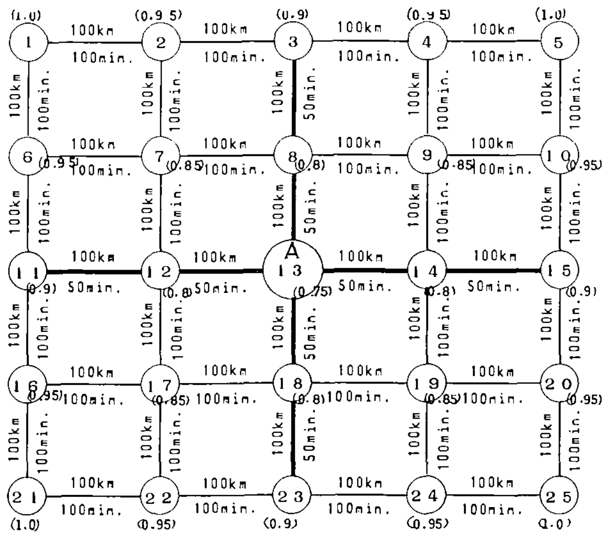
$$G_i = \frac{\bar{G}\, AC_{1i}^{\lambda_1} AC_{2i}^{\lambda_2}}{\sum_k AC_{1k}^{\lambda_1} AC_{2k}^{\lambda_2}}, \quad (i=1,---,n) \; . \tag{29}$$

In practice, equation (28) is very convenient for illustration of interesting properties of the spatial equilibrium model to be discussed as follows.

3.3 Numerical Examples

In order to probe some of the basic properties of the above model, it may suffice to consider a simplified network which involves twenty-five nodes (cities). The compact geography for this situation is depicted in Figure 2. The relative cost to get the local resources, i.e. Ψ_i^* and the data for the network are also described in Figure 2. Each link is equipped with dual network modes, i.e. telecommunication and transportation modes. A total of 200 units of knowledge handling workers is to be allocated to the whole nodes of the network. The network can be characterized by the spatial configuration of a gigantic city, i.e. Node A and many local cities. Node A is the major junction of the high-speed transportation (Shinkansen) network. Local cities have relative advantages in the factor prices of local material resources such as labour force and capitals. For the moment, let us assume that R & D facilities in the public sector are distributed uniformly over the network; the scale of R & D facilities for each node is supposed to take the same value, i.e. $W_j = 1.0$ $(j=1,---,25)$.

Fig. 3 illustrates what will happen to the regional division of knowledge labour force in two cases where the values of parameters of knowledge



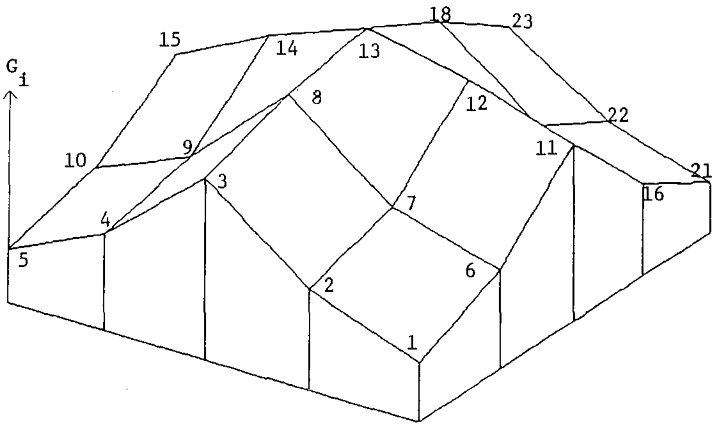
$\beta_1=0.0001, \beta_2=0.01$

Numerals in parentheses show the value of Ψ_i of corresponding nodes.

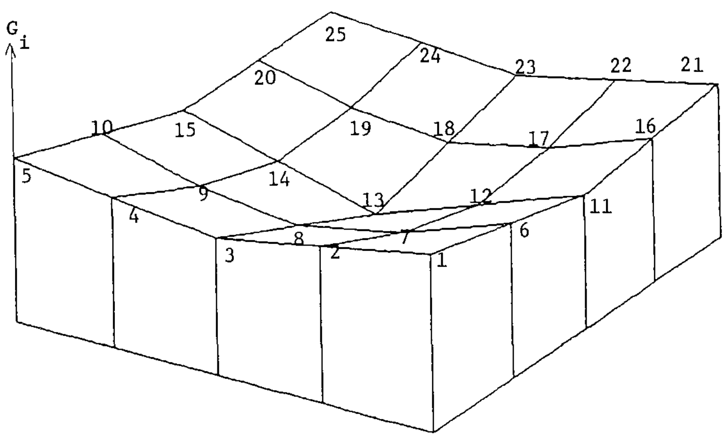
Fig. 2 A Hypothetical Network

production function are fixed as follows: (1) λ_1 = 0.01, λ_2 = 1.20 (Case 1), (2) λ_1 = 1.0 , λ_2 = 0.01 (Case 2). Firms' knowledge production requires the highly developed face-to-face accessibility to knowledge in Case 1. On the other hand, they are largely dependent upon the information exchanges through telecommunication network in Case 2. For both cases, it is obvious that the network structure has a significant influence on regional divisions of workers. In Case 1, our system bears agglomeration cores of knowledge production within the discrete network. The central node (Node A) has the best precondition for the development of knowledge, since it enjoys a highly developed accessibility to knowledge on both networks. In Case 2, knowledge handling labour forces are decentralized even to the peripheral nodes. This is because the spread of telecommunications increases the accessibility of information for the peripheral nodes. The production of goods and knowledge, which is largely dependent upon the transmission of uncomplicated and routinized information is facilitated to decentralize in Case 2, because of the increased possibilities of substitution of human contacts for the transmission of data and information.

It is interesting, and possible, to explore how knowledge production technology may have major impacts on the regional division of knowledge workers. Examples of possible states for regional divisions of knowledge labour



1) Case 1 (λ_1=0.01, λ_2=1.2)



2) Case 2 (λ_1=1.0, λ_2=0.01)

Fig. 3 Spatial Equilibria of Knowledge Production

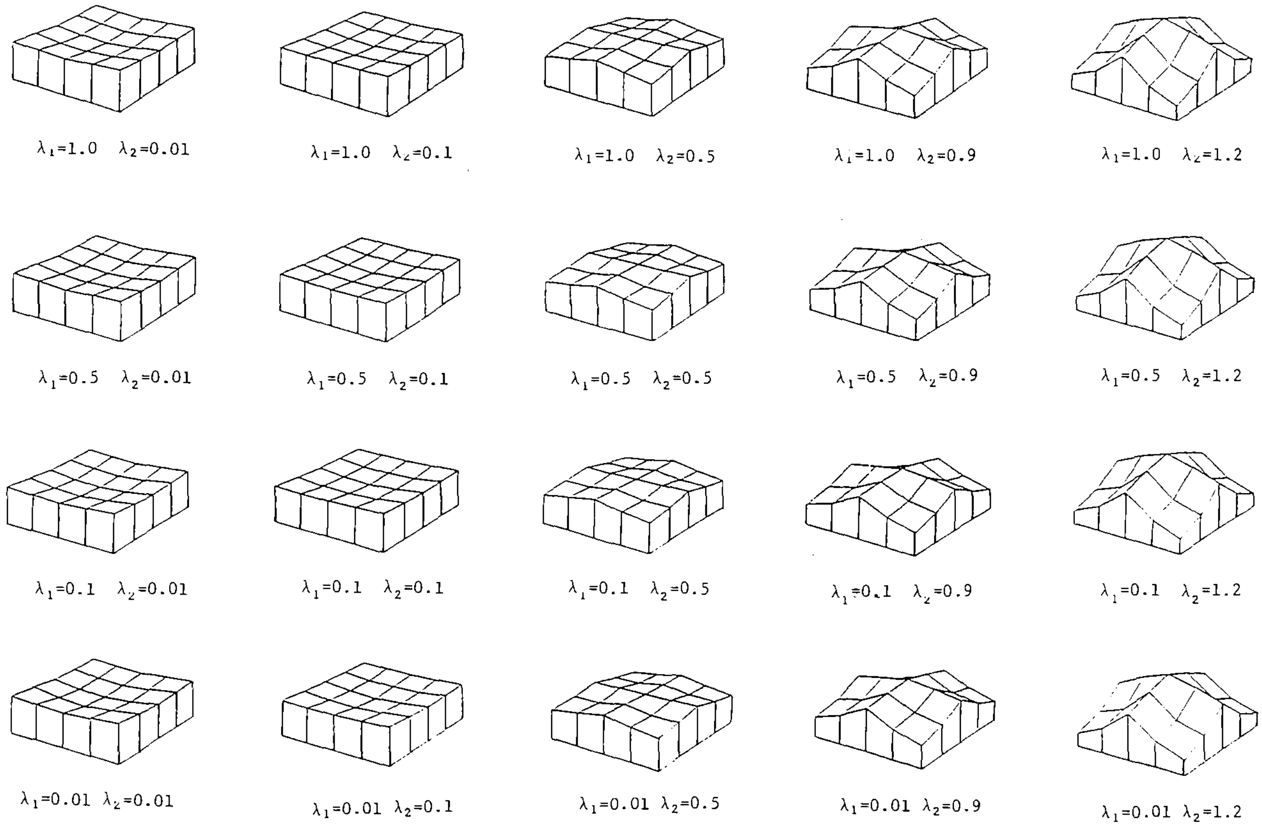


Fig. 4 Qualitative Transitions between Spatial Equilibria

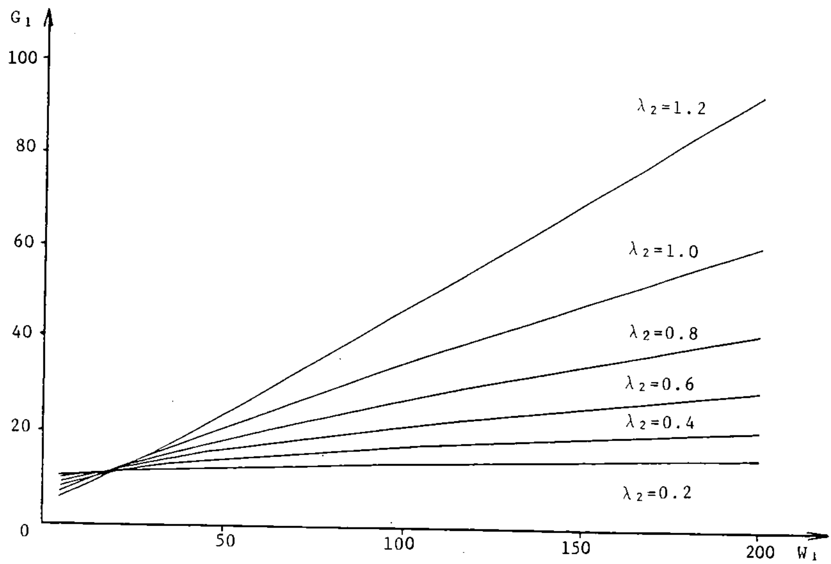


Fig. 5 Share of Knowledge workers in Node 1 (λ_1 = 0.5)

force as a function of two parameters can also be studied (λ_1 and λ_2 represent the elasticity of knowledge output with respect to the telecommunication and face-to-face accessibility measures, respectively). The larger λ_1, the more important is the telecommunication accessibility; the larger λ_2, the more significant is the face-to-face synergy in knowledge exchange. Fig. 4 explains transformations between equilibria of knowledge production. As λ_2 becomes larger, firms tend to concentrate more to the center node; as λ_1 becomes larger, knowledge workers can be more decentralized to the periphery. Some of the ramification of the numerical results sketched above warrant brief explanation. The face-to-face accessibility is a precondition for synergetic relations between knowledge workers. The spread of telecommunications, which increases the accessibility of information for the regions of the periphery, may have no significant effect on the decentralization of more advanced R & D activities. The increased telecommunication accessibility is primarily for the transmission of uncomplicated and routinized information. Such communications as complicated as negotiations and the transmission of new knowledge and competence will require direct contacts among people. The center of the face-to-face accessibility possesses the strong preconditions to incubate the new knowledge and more advanced R & D activities.

Fig. 5 illustrates how the relative shares of knowledge workers in the peripheral node (Node 1), changes, if its capacities of research units W_1 vary.

If the value of W_1 increases due to the opening of new research units, the value of G_1 rises rather slowly. The increasing rates of G_1 with respect to W_1 are largely dependent upon the value of the parameter λ_2. The more sensitive to the face-to-face-accessibility firms' R & D technology becomes, the larger becomes the increasing rate of G_1. Fig. 5 illustrates that those nodes which are facilitated to develop and maintain a research-rich development policy by providing highly qualified research centers, are most likely to enjoy technological leadership to some extent if knowledge production technology is sensitive to face-to-face accessibility. Thus, in the expected transition towards a knowledge-based society in the near future, there is evidence to suggest that knowledge infrastructure might play an essential role in the enhancement of the productivity of knowledge and goods. So it may well be concluded that this type of infrastructure will become increasingly important determinants for regional divisions of knowledge production.

4. CONCLUSION

It is important to understand how knowledge-based inputs interact with conventional inputs in the production process, and how knowledge is exchanged and enhanced. This paper has treated stocks of knowledge as endogenous public goods. Knowledge expands and is enhanced by way of exchange processes across a network which consists of R & D nodes and transportation/telecommunication links in space. A production function for knowledge is derived in terms of the size of each node's knowledge-handling workforce and its aggregate level of accessibility to knowledge stocks throughout the network. The optimal R & D policy for each node is heavily dependent on the two attributes of its knowledge workforce. Non-cooperative behaviors result in a Nash equilibrium solution to the spatial equilibrium problem. A simple numerical illustration has been presented to demonstrate how regional divisions of knowledge labour force are dependent upon the knowledge production technology and knowledge infrastructure.

Although still remote from a complete theory of technological substitution of telecommunications and transportation in knowledge production, this paper addresses to some basic components that may describe the essential mechanism of the regional divisions of knowledge labour force, given a single type of agents. We believe that structural forms for the interdependencies between knowledge workers may be constructed in line with the mathematical formulation presented in this paper. Further research is still needed, however, in order to develop a more comprehensive theory on the regional divisions of knowledge labour force. Further items of interest which have not yet been considered include:

(a) to consider more general classes of production functions appropriate to investigate technological substitution between transportation and telecommunication in production;

(b) to investigate the self-organizing character of the dynamic model of knowledge distribution;

(c) to introduce nonlinear accessibility functions which allow for such phenomena as economies of scale or decreasing knowledge returns from congested networks; and

(d) to develop appropriate investment functions to represent the response patterns to changing relative demands for nodal and network infrastructures to facilitate further knowledge expansion.

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