Regional Specialization via Differences in Transport Costs*

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Abstract

Regional specialization via differences in transport costs is observed in Japanese manufacturing industries. For example, industries with high transport costs for their products, such as iron & steel and petroleum & coal products, have remained close to the core region, while industries with low transport costs, such as electrical machinery and precision instruments, have relocated to the periphery region. The objective of this study is to provide a theoretical foundation for this fact by use of a new economic geography model with multiple industries and urban costs. The following results were obtained. First, although dispersion of industries can be brought by either large commuting costs or small transport costs, their dispersion patterns are different: the former definitely result in full dispersion, while the latter might bring (complete or partial) regional specialization. Second, an industry with a higher transport cost might occupy a lower share in the bigger region than an industry with a lower transport cost in order to avoid the severer competition.

Key words: regional specialization, economic geography, transport costs, urban costs, competition effects.

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1 Introduction

During the past four decades, many Japanese manufacturing industries have spread from the "core" region to the "periphery" region.[1] Figures 1a and 1b show changes of regional shares in value of products and in employment, respectively. In 1960, Japanese manufacturing produced (resp. absorbed) nearly 55% (resp. 50%) of the product value (resp. workers) in the core, but in 2000, only 35% (resp. 30%) of the product value (resp. workers) were produced (resp. absorbed) in the core.

Not all manufacturing industries are similarly dispersed, but they differ in degree according to their transport features. Usually, industries such as transport equipment, printing & publishing, petroleum & coal products, and iron & steel are with high transport costs, while industries such as electrical machinery and precision instruments are with low transport costs.[2] Figure 2 shows that the industries with high transport costs have remained close to the core, while the industries with low transport costs have considerably relocated to the periphery.[3] More specifically, concerning precision instruments, 75% of them were produced in the core in 1960 but only 32% in 2000, when the periphery share (35%) exceeded the core share. On the other hand, concerning petroleum & coal products, for example, regional shares have remained nearly constant since 1960.

Differences in changes of industrial locations can be viewed as a consequence of regional policies aiming to attract new industries with high value added, such as industries related to electrical and information technology (IT). Such industries are called "close-to-airport industries" since their products can be conveniently transported by airplanes, and some Japanese regional governments (e.g., Ishikawa Prefecture, Chitose City, Kitakyushu City) are actually inviting such industries by improving the facilities at their local airports.

We do not deny the possibility that such regional policies in the periphery brought the asymmetric industrial location, i.e., regional specialization via differences in transport costs. In

[1] According to Fujita and Hisatake (1999) and Fujita *et al.* (2004), 47 Japanese prefectures are divided into three macroregions as follows: *Core* consists of Tokyo and Kanagawa (the core of the Tokyo Metropolitan Area [MA]), Aichi (containing Nagoya MA), Osaka and Hyogo (the core of the Osaka MA); *Semi-Core* consists of the Pacific Industrial Belt excluding the Core (18 prefectures), and *Periphery* is the rest of Japan.

[2] For example, Glaeser and Kohlhase (2004) provide some data for the US industries. In Table 1 of page 206, the values per ton ($) of several industries, which are expected to be in inverse proportion to their transport costs, are as follows: Gasoline and aviation turbine fuel, 225; Base metal (in primary or semi-finished forms and in finished basic shapes), 851; Printed products, 3335; Motorized and other vehicles (including parts), 5822; Electronic and electrical equipment, components and office equipment, 21955.

[3] By the regional shares in product value from the latest Japanese Census of Manufactures in 2000, 21 types of manufacturing industries are divided into the following four categories: (a) *Core-oriented industries* [Core>Semi-Core>Periphery]: General machinery, Transportation equipment, Printing & publishing, Leather & leather products (4 types); (b) *Semi-core-oriented industries I* [Semi-Core>Core>Periphery]: Chemicals, Petroleum & coal products, Plastic, Rubber, Iron & steel, Non-ferrous metals, Fabricated metal products (7 types); (c) *Semi-core-oriented industries II* [Semi-Core>Periphery>Core]: Processed foods, Textiles, Apparel, Lumber & wood, Furniture, Paper & pulp, Ceramics, stone, clay, and glass (7 types); (d) *Periphery-oriented industries* [Periphery>Semi-Core>Core]: Electrical machinery, Precision instruments, Beverage, forage, and tobacco (3 types).

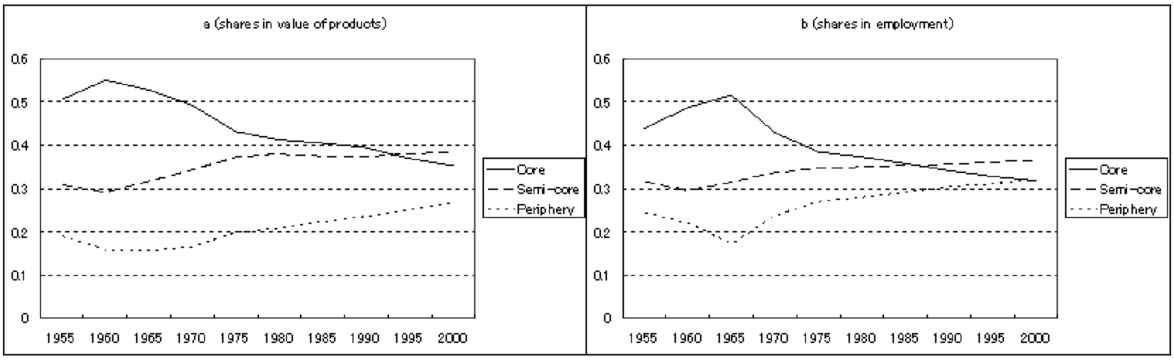

Figure 1: Changes in regional shares (all manufactures). *Source*: Japanese Census of Manufactures

this study, however, we show that regional specialization occurs even if regions are symmetric without heterogeneous policies.

Our framework is based on and extends the new economic geography (NEG) model of Ottaviano, Tabuchi and Thisse (2002). NEG models originated by Krugman (1991) have successfully clarified the relationship between transport costs and industrial location; however, regional specialization of individual industries has not yet been explained in the NEG literature because most researchers assume that there is only one industry in the manufacturing sector for simplicity. To fill this theoretical gap, in this study, an NEG model is established with multiple industries, which are expected to clarify how different industries present different location patterns when the transportation system improves.

The model presented here is roughly outlined as follows. The industries are differentiated by their transport costs for their products. As in most NEG models, we assume the consumers' love for variety and increasing returns at the firm level as the agglomeration force (Krugman, 1991). On the other hand, the dispersion force is supposed to be urban costs, i.e., housing and commuting costs (Krugman and Livas Elizondo, 1996; Tabuchi, 1998; Helpman, 1998). The distribution of industries is determined by the balance of these two forces. Based on one-industry models, Tabuchi (1998) and Helpman (1998) found that, when the transport costs of manufacturing goods are small, the industrial location shifts from agglomeration to dispersion since the urban costs become relatively large. In our model of multiple industries, the dispersion process is more specific: in a space with a sufficiently developed transportation system, industries with lower transport costs tend to leave the core for the periphery.

Some researchers have considered similar multi-industry location problems based on NEG. From the viewpoint of international economics, Puga and Venables (1996) and Krugman and Venables (1997) have examined the situation of multiple industries. These studies succeeded in describing the international spread of industry due to the increasing demand of manufacturing

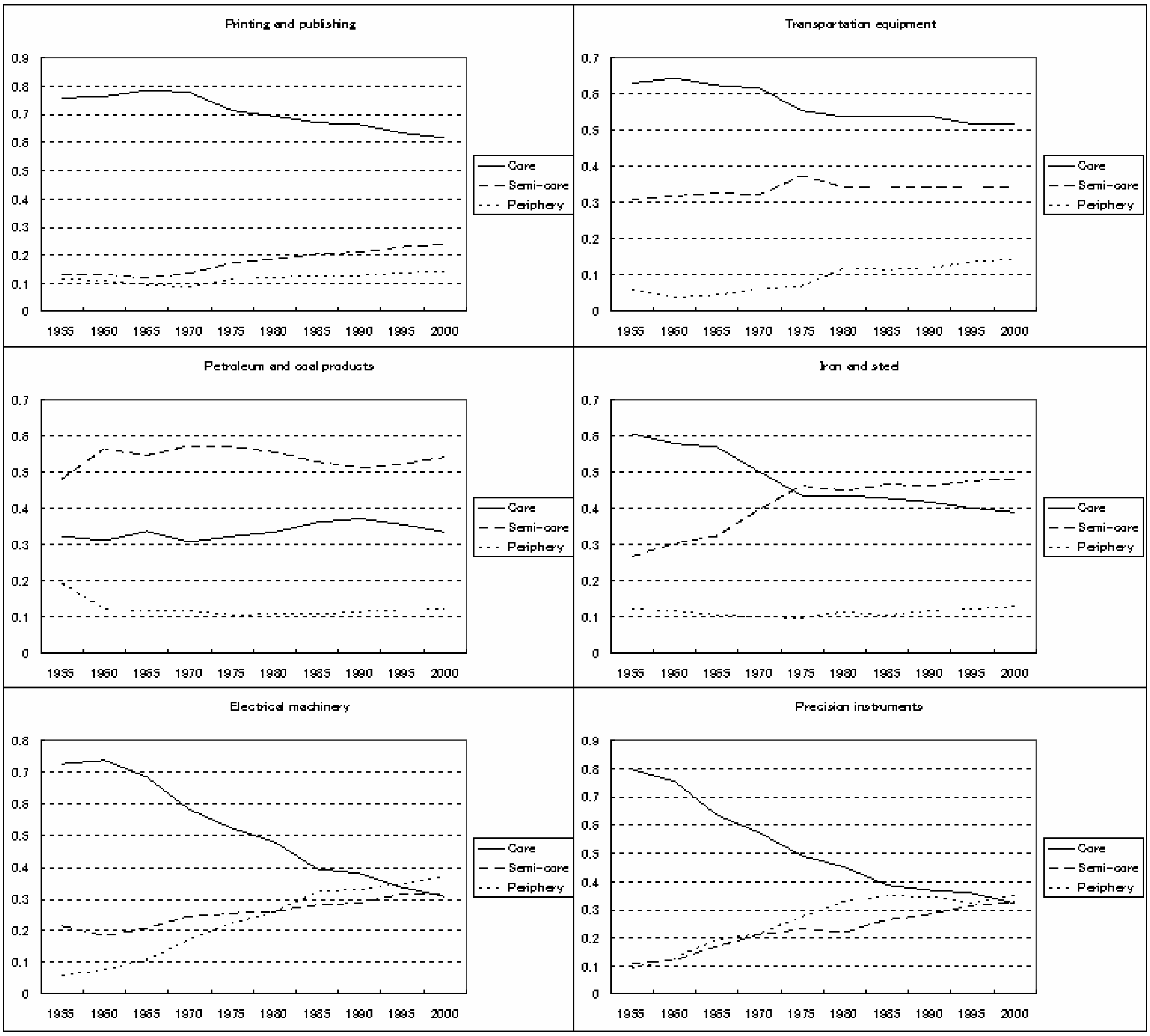

Figure 2: Changes in regional shares in value of products. *Source*: Japanese Census of Manufactures

goods and the industrial clustering due to decreasing trade costs, respectively. However, workers are supposed to be immobile in their models, so their results are restricted to international situations. Fujita, Krugman, and Mori (1999) first find multiple industries form a hierarchical urban system when the whole population increases. Their model assumes a continuous space in which residents are mobile. Although industries are differentiated by their transport costs, the costs are supposed to be constant there.

Recently, Tabuchi and Thisse (2003) also investigated the location patterns of industries with different transport costs and urban costs. Their analysis is limited to the case of two industries with changing commuting costs only. A recent paper of Zeng (2005) similarly described regional specialization by a model of multiple industries, which is different from ours in two respects. First, Zeng (2005) differentiates industries by the numbers of unskilled workers necessary in their production, and all industries are supposed to have the same transport costs. In contrast, we differentiate the industries by their transport costs here. Second, the dispersion force of Zeng (2005) is from the agricultural sector, while the dispersion force here is from urban costs. Therefore, two models are considered to reveal the evolution process of a multi-industry manufacturing sector in a complimentary way.

Two primary results are derived from the present study. First, although dispersion of industries can be brought by either sufficiently large commuting costs or sufficiently small transport costs, their dispersion patterns are different: the former result in full dispersion, but the latter might bring (complete or partial) regional specialization. Second, we find that an industry with a higher transport cost might occupy a lower share in the bigger region than an industry with a lower transport cost. It seems contradictory to the intuition since industries with higher transport costs can reduce more costs by locating in the bigger market. But this fact can be explained by the competition effect, which is a dispersion force working more strongly for industries with higher transport costs.

The remainder of this paper is organized as follows. The NEG model is established in Section 2 with multiple industries in the manufacturing sector and the four effects determining utility differentials in the model are clarified in Section 3. Limiting to the three-industry case, typical location patterns are analytically examined in Section 4. Section 5 shows some numerical simulations which support the results of Section 4. Finally, Section 6 summarizes the conclusions.

2 The model

The economy has two symmetric regions, called H and F, and K industries. There are three types of goods: an initially endowed homogeneous good, which is chosen as the numéraire, differentiated varieties produced by firms in the industries under increasing returns technology, and land. Each industry supplies a continuum N of differentiated varieties, where N is the same for all industries. Since there is no scope of economies due to increasing returns technology, there is also a continuum N of firms.

Firms use only labor for their production. Similar to Krugman (1981) and Zeng (2005), we assume that there are K types of workers corresponding to K types of industries and each industry employes its own workers only. This is justified by the fact that modern industries depend on peculiar and special technologies, and workers choose jobs according to their educational experience and abilities. Furthermore, we suppose that the number (measure) of each type of workers is the same L. On the other hand, although the workers are immobile among industries, they are mobile between regions. In other words, workers relocate without any costs.

Land is used by workers, rather than firms, for their housing. More precisely, each region has its central business district (CBD) as a point, and all firms in the region locate there. The space is linearly distributed around the CBD, and each location has one unit amount of land. Each worker consumes one unit amount of land for residing and commutes to the CBD. In addition, it is assumed that the commuting costs per unit of distance are θ units of the numéraire, the opportunity cost of land is normalized to zero, and the total land rent of one region is evenly distributed among all residents in the region. Under these assumptions, the net urban cost (i.e., land rent payment+commuting costs−land rent revenue) per worker is given by $(\theta/4)\times$(population in the region).

Generalizing the framework of Ottaviano, Tabuchi and Thisse (2002) to multiple types of industries, workers are assumed to hold the same preference, which are described by a quasi-linear utility with quadratic subutility:

$$U_r(q_0, q_{kr}(j), j \in [0, N], k = 1, \cdots, K) = \sum_{k=1}^{K} \Bigg[\alpha \int_0^N q_{kr}(j) dj - \frac{(\beta-\gamma)}{2K} \int_0^N [q_{kr}(j)]^2 dj - \frac{\gamma}{2KN} \left(\int_0^N q_{kr}(j) dj \right)^2 \Bigg] + q_0, \tag{1}$$

where q_0 stands for the consumption of the homogeneous good and $q_{ir}(j)$ is the consumption of variety $j \in [0, N]$ in industry i for workers in region r $(= H, F)$. We assume that $\alpha > 0$ and $\beta > \gamma > 0$, which means that this utility function represents the workers' love for variety.

Each worker in region r maximizes their utility (1) under budget constraints

$$\sum_{k=1}^{K} \left[\int_0^N p_{kr}(j) q_{kr}(j) dj + \frac{\theta}{4} L_{kr} \right] + q_0 = w_{kr} + \overline{q}_0,$$

where $p_{ir}(j)$ is the price of variety j in industry i for workers in region r, and where L_{ir} and w_{ir} are the number (measure) of workers and the wage of workers in industry i and region r, respectively. Finally, $\overline{q}_0$ is the quantity of the initially endowed homogeneous good, which is supposed to be sufficiently large for the equilibrium consumption q_0 of the numéraire to be positive.

Workers' utility maximization gives the following individual demand function, $q_{ir}(j)$, and indirect utility function V_{ir} for for workers in industry i in region r:

$$q_{ir}(j) = K\left[a - bp_{ir}(j) + c\frac{P_{ir}}{N}\right], \quad j \in [0, N], \tag{2}$$

$$V_{ir} = KN\left[\frac{Ka^2}{2(b-c)} - \frac{a}{N}\sum_{k=1}^{K} P_{kr} + \frac{b}{2N}\sum_{k=1}^{K}\int_0^N \{p_{kr}(j)\}^2 dj - \frac{c}{2N^2}\sum_{k=1}^{K}(P_{kr})^2\right] + w_{ir} + \overline{q}_0 - \frac{\theta}{4}\sum_{i=k}^{K} L_{kr},$$

where $a \equiv \alpha/\beta$, $b \equiv 1/(\beta - \gamma)$, $c \equiv \gamma/[\beta(\beta-\gamma)]$, and $P_{ir} \equiv \int_0^N p_{ir}(j)dj$ is the price index of industry i in region r. Since $\beta > \gamma > 0$, we have $b > c > 0$.

Each firm produces a differentiated variety in a monopolistically competitive way, and each firm is negligible, so its pricing has no influence on the price index P_{ir} in (2). Since all industries are of the same size and all types of workers are of the same population, firms employ the same number of workers in their production. For simplicity, we normalize the unit of workers so that each firm employs one unit of workers i.e., $N = L$. The interregional transport costs of varieties are different between industries, and the transport cost of one unit of a variety in industry i is denoted by τ_i. Under these assumptions, all firms in the same industry and the same region are symmetric, and a typical firm in industry i and region r maximizes the following profit:

$$\Pi_{ir} = p_{irr}q_{irr}(p_{irr})\sum_{i=1}^{K} L_{ir} + (p_{irs} - \tau_i)q_{irs}(p_{irs})\sum_{i=1}^{K} L_{is} - w_{ir},$$

where q_{irs} and p_{irs} are the individual demand and the price in region s for firms of industry i and located in region r, and L_{ir} is the number of workers in industry i in region r:

The FOC of the profit maximization and the assumption of free entry give the following equilibrium price and wage:

$$p^*_{irr} = \frac{2a + c\tau_i(L_{is}/L)}{2(2b-c)}, \; p^*_{irs} = p^*_{iss} + \frac{\tau_i}{2},$$

$$w^*_{ir} = bK\left[(p^*_{irr})^2\sum_{k=1}^{K} L_{kr} + (p^*_{irs} - \tau_i)^2\sum_{k=1}^{K} L_{ks}\right].$$

It should be noted that p^*_{irr} rises with decreasing $L_{ir} = L - L_{is}$ since the competition in industry i and in region r becomes milder. Furthermore, the degree is larger for industries with higher transport costs, because the competition with imported goods is milder. In fact, the price differentials between domestic goods and imported goods are half of their transport costs.

From these equations, the utility differential between two regions for workers of industry i is obtained:

$$V_{iH} - V_{iF} = (S_H - S_F) + (w^*_{iH} - w^*_{iF}), \tag{3}$$

$$S_H - S_F = \sum_{k=1}^{K}(\frac{1}{2} - \lambda_k)\left[b^2\overline{L}\frac{(b-c)\tau_k^2 - 2a\tau_k}{(2b-c)^2} + \frac{L\theta}{2}\right], \tag{4}$$

$$w_{iH}^* - w_{iF}^* = b\overline{L}\left[\frac{(b-c)\tau_i^2 - 2a\tau_i}{2b-c}\sum_{k=1}^{K}(\frac{1}{2} - \lambda_k) + (\frac{1}{2} - \lambda_i)\frac{cK\tau_i^2}{2(2b-c)}\right]. \tag{5}$$

where S_r is the consumer's surplus in region r, λ_i is the share of workers of industry i residing in H, L_{iH}/L, and $\overline{L}$ is the total number of workers, KL.

We now assume that $\tau_i = \omega_i\tau$, for simplicity, where $\tau(>0)$ stands for transport technology. This means that transport costs for all industries proportionally decrease with the progress in transportation technology (decreasing τ). Furthermore, we assume $\omega_i \neq \omega_j$ for any different i and j, and the industries are named such that

$$\omega_1 > \omega_2 > \cdots > \omega_K.$$

For trade to occur in all industries regardless of the location patterns, it should hold that $\tau < \tau_{trade} \equiv 2a/\{\omega_1(2b-c)\}$, which is assumed to be true in the following analysis.

Under these assumptions, the utility differential $V_{iH} - V_{iF}$ is rewritten as

$$\begin{aligned} V_{iH} - V_{iF} =& (\frac{1}{2} - \lambda_i)\left[\omega_i^2\nu_1 - \omega_i\nu_2 + \frac{L\theta}{2}\right] \\ &+ \sum_{j\neq i}(\frac{1}{2} - \lambda_j)\left[\omega_j^2\mu_1 - \omega_j\mu_2 + \omega_i^2\xi_1 - \omega_i\xi_2 + \frac{L\theta}{2}\right] \\ =& \sum_j(\frac{1}{2} - \lambda_j)\delta_{ij}, \end{aligned} \tag{6}$$

where

$$\nu_1 \equiv \frac{bK\tau^2}{2(2b-c)^2}\left[(2bc-c^2)(\overline{L}-L) + (6b^2-6bc+c^2)L\right],\ \nu_2 \equiv \frac{2ab(3b-c)}{(2b-c)^2}\overline{L}\tau,$$

$$\mu_1 \equiv \frac{b^2(b-c)}{(2b-c)^2}\overline{L}\tau^2,\ \mu_2 \equiv \frac{2ab^2}{(2b-c)^2}\overline{L}\tau,\ \xi_1 \equiv \frac{b(b-c)}{2b-c}\overline{L}\tau^2,\ \xi_2 \equiv \frac{2ab}{2b-c}\overline{L}\tau,$$

$$\delta_{ij} \equiv \begin{cases} \omega_i^2\nu_1 - \omega_i\nu_2 + \frac{L\theta}{2}, & \text{if } i = j, \\ \omega_j^2\mu_1 - \omega_j\mu_2 + \omega_i^2\xi_1 - \omega_i\xi_2 + \frac{L\theta}{2}, & \text{if } i \neq j. \end{cases} \tag{7}$$

Finally, the following dynamic system is employed to describe the migration behavior between regions.

$$\frac{d\lambda_i}{dt} = V_{iH}(\boldsymbol{\lambda}) - V_{iF}(\boldsymbol{\lambda}) = \sum_j(\frac{1}{2} - \lambda_j)\delta_{ij}. \tag{8}$$

3 Region size and utility diffenrentials: four effects

To see how the population in region H changes the consumer's surplus differential and the wage differential, we rewrite (4) and (5) as follows:

$$S_H - S_F = \frac{b^2\overline{L}}{(2b-c)^2}\sum_{k=1}^{K}\left(\lambda_k - \frac{1}{2}\right)F_k(\tau) - \frac{L\theta}{2}\sum_{k=1}^{K}\left(\lambda_k - \frac{1}{2}\right), \tag{9}$$

$$w_{iH}^* - w_{iF}^* = \frac{b\overline{L}}{2b-c}F_i(\tau)\sum_{k=1}^{K}\left(\lambda_k - \frac{1}{2}\right) - \frac{bcK\overline{L}\omega_i^2\tau^2}{2(2b-c)}\left(\lambda_i - \frac{1}{2}\right), \tag{10}$$

where $F_i(\tau) \equiv 2a\omega_i\tau - (b-c)\omega_i^2\tau^2$. We can easily show that, when $\tau \in (0, \tau_{trade})$, $F_i(\tau)$ is positive and monotone increasing with respect to τ and $F_i(\tau) > F_j(\tau)$ iff $i < j$.

If population increase in region H, then firms and the varieties produced in the region also increase. Thus the market access for residents in the region is improved, which increases the consumer's surplus differential, $S_H - S_F$. This effect is expressed by the first term in (9), which we call the *market-access effect on consumers*. We should note that the whole market-access effect of all industries is not always positive even if more than half of the *total* workers reside in region H, because increasing the population of an industry may not improve the market access if many industries with high transport costs locate in the other region. However, it is sufficient for this effect being positive that in *each industry* more than half of its workers reside in region H, i.e., $\lambda_i > 1/2$ $(i = 1, \cdots, K)$. On the other hand, increasing population in region H must increase urban costs in the region, which decreases $S_H - S_F$. This effect is expressed by the second term in (9), which we call the *urban-cost effect*. It is negative iff more than half of the total workers reside in region H. Depending on the balance of these two effects, increasing population in region H may either increase or decrease $S_H - S_F$.

If population increase in region H, then the market access for producers in the region is also improved and the wage differentials of each industry, $w_{iH}^* - w_{iF}^*$ $(i = 1, \cdots, K)$, increase. This effect is expressed by the first term in (10), which we call the *market-access effect on firms*. It is clearly positive iff more than half of the whole population reside in region H. In addition, this effect is stronger for industries with higher transport costs since $F_i(\tau) > F_j(\tau)$ iff $i < j$. It means that such industries can reduce more costs by locating in the bigger market. On the other hand, increasing the population (and firms) of industry i residing region H must make the competition of price reduction in industry i severer, which decreases $w_{iH}^* - w_{iF}^*$. This effect is expressed by the second term in (10), which we call the *competition effect*. It is negative for industry i iff more than half of the workers in industry i reside in region H. It should be noted that this effect is also stronger for industries with higher transport costs since such industries can set higher prices by leaving a competitive region. As a result, depending on the balance of these two effects, increasing population in region H may either increase or decrease $w_{iH}^* - w_{iF}^*$.

Finally, we check how decreasing τ or increasing θ influences the above four effects and the allocation of workers between two regions. At first, decreasing τ weakens all of the four effects. Furthermore, if τ is small, then the urban cost effect dominates since the two market-access effects and the competition effect becomes much smaller. Thus the utility in the bigger region decreases while the utility in the smaller region increases so that workers move to the smaller region. As a result, the populations in two regions become close. On the other hand, increasing θ strengthens only the urban cost effect. Therefore, if θ is large enough, then this effect also dominates and the populations become close again.

Then, are these two dispersion processes different from each other? The next section gives an affirmative answer.

4 Industrial location

In this section, we analytically investigate how the stability of a location pattern depends on the two dispersion forces of decreasing τ and increasing θ. For simplicity, we specify $K = 3$, which is sufficient to describe regional specializations. In addition, to clarify the location patterns, we focus on the equilibria in which the population in region H is larger than or equal to the population in region F.

Since the populations in two regions are close if τ is small enough or θ is large enough, it becomes impossible for more than two industries to agglomerate in a single region (e.g., location patterns $\boldsymbol{\lambda}^* = (1, 1, 1)$, $(1, 1, \lambda_3^*)$, and $(1, 1, 0)$ are impossible). In other words, the following three location patterns are the only possible distributions, where $0 < \lambda_1^* < 1$, $0 < \lambda_2^* < 1$, and $0 < \lambda_3^* < 1$, if τ is small enough or θ is large enough:[4]

(A) *full dispersion*: all industries disperse ($\boldsymbol{\lambda}^* = (\lambda_1^*, \lambda_2^*, \lambda_3^*)$);

(B) *complete regional specialization*: one industry disperses, while the others agglomerate in different regions, ($\boldsymbol{\lambda}^* = (\lambda_1^*, 1, 0)$, $(1, \lambda_2^*, 0)$, $(1, 0, \lambda_3^*)$);

(C) *partial regional specialization*: two industries disperse, and the remaining one agglomerates in a region ($\boldsymbol{\lambda}^* = (1, \lambda_2^*, \lambda_3^*)$, $(\lambda_1^*, 1, \lambda_3^*)$, $(\lambda_1^*, \lambda_2^*, 0)$).

Let

$$\overline{\theta}_0 \equiv \frac{16a^2b^2}{c(2b-c)^2}\frac{\omega_1^2(\omega_2-\omega_3)^2+\omega_2^2(\omega_3-\omega_1)^2+\omega_3^2(\omega_1-\omega_2)^2}{\omega_1^2\omega_2^2+\omega_2^2\omega_3^2+\omega_3^2\omega_1^2},$$

$$\overline{\theta}_1 \equiv \frac{16a^2b^2}{c(2b-c)^2}\frac{(\omega_1-\omega_2)(\omega_1-\omega_3)}{\omega_1^2},$$

$$\overline{\theta}_2 \equiv \frac{16a^2b^2}{c(2b-c)^2}\frac{(\omega_1-\omega_3)(\omega_2-\omega_3)}{\omega_3^2},$$

[4]By the symmetry of regions, symmetry patterns like $(\lambda_1^*, 1, 0)$ and $(\lambda_1^*, 0, 1)$ are considered to be the same.

$$\overline{\omega}_2 \equiv \frac{\omega_3^2}{\omega_1^2+\omega_3^2}\omega_1 + \frac{\omega_1^2}{\omega_1^2+\omega_3^2}\omega_3,$$

and note that all of these parameters are positive since $\omega_1 > \omega_2 > \omega_3$. It also holds that $\overline{\theta}_0 > \min\{\overline{\theta}_1, \overline{\theta}_2\}$.[5] For convenience, we exclude some parameter values of measure 0 in the whole parameter space by assuming that

$$\begin{aligned} &\theta \neq \overline{\theta}_0, \overline{\theta}_1, \overline{\theta}_2 \\ &\omega_2 \neq \bar{\omega}_2. \end{aligned} \tag{11}$$

The following proposition specifies how the location pattern depends on θ when τ is small. It tells us that for a sufficiently small τ, location patterns (A), (B), and (C) do not occur simultaneously for any θ.

Proposition 1 *(Regional specialization) For a sufficiently small τ,*

(i) $\boldsymbol{\lambda}^* = (1/2, 1/2, 1/2)$ is the unique stable equilibrium iff $\theta > \overline{\theta}_0$,

(ii) $\boldsymbol{\lambda}^* = (\lambda_1^*, \lambda_2^*, 0)$ is the unique stable equilibrium iff $\min\{\overline{\theta}_1, \overline{\theta}_2\} < \theta < \overline{\theta}_0$, and $\omega_2 > \bar{\omega}_2$,

(iii) $\boldsymbol{\lambda}^* = (1, \lambda_2^*, \lambda_3^*)$ is the unique stable equilibrium iff $\min\{\overline{\theta}_1, \overline{\theta}_2\} < \theta < \overline{\theta}_0$, and $\omega_2 < \bar{\omega}_2$,

(iv) $\boldsymbol{\lambda}^* = (1, \lambda_2^*, 0)$ is the unique stable equilibrium iff $\theta < \min\{\overline{\theta}_1, \overline{\theta}_2\}$,

where $\lambda_i^* \in (0, 1)$ for all $i = 1, 2, 3$.

Proof. See Appendices A, B and C. ■

If τ is small enough, all industries disperse evenly for a sufficiently large θ, but, as θ decreases, partial regional specialization first emerges, and then complete regional specialization occurs. Specifically, (i) when ω_2 is relatively large and close to ω_1, industry 3 first agglomerates in a region, and industry 1 then agglomerates in the other region. On the other hand, (ii) when ω_2 is relatively small and close to ω_3, industry 1 first agglomerates in a region, and industry 3 then agglomerates in the other region. In both cases, when θ is small enough, industry 1 and industry 3 agglomerate in different regions.

We should note that industries with higher transport costs never occupy a lower share in the bigger region (H) than those with lower transport costs for a sufficiently small τ. For example, we know that $\lim_{\tau\to 0} \lambda_2^* > \lim_{\tau\to 0} \lambda_3^*$ and $\lambda_2^* + \lambda_3^*$ converges to 1/2 from above in equilibrium $(1, \lambda_2^*, \lambda_3^*)$ [see the end of Appendix C] and that λ_2^* converges to 1/2 from above in equilibrium $(1, \lambda_2^*, 0)$ [see Appendix B]. This result might be intuitive since industries with higher transport costs can reduce more costs by locating in the bigger market. However, it is not true for any $\tau \in (0, \tau_{trade})$. It will be discussed in detail in Section 5.

Although Proposition 1 focus only on the case of small τ, the location patter $(1/2, 1/2, 1/2)$ of (i) is stable for quite general τ if θ is large. Specifically, we have the following proposition:[6]

[5] See Appendix C.

[6] This result resembles Proposition 3 in Tabuchi and Thisse (2003), in which they assume $K = 2$ but consider inter-industry mobility.

Proposition 2 *For a sufficiently large θ, $\boldsymbol{\lambda}^* = (1/2, 1/2, 1/2)$ is the unique stable equilibrium.*

Proof. See Appendix D. ■

As shown in Proposition 1 and 2, decreasing τ can bring (complete or partial) regional specialization, but increasing θ definitely result in full dispersion. Why does such a difference occur? Here, we pick up the complete specialization equilibrium $\boldsymbol{\lambda}^* = (1, \lambda_2^*, 0)$, and see how the changes of τ and θ makes this location pattern stable or unstable via the four effects discussed in Section 3.[7]

Why does increasing θ make the specialization unstable?

From (10), we know the wage differential of workers in industry 2, $w_{2H}^* - w_{2F}^*$, is close to zero, since the two populations are close for a sufficiently large θ (i.e., $\lim_{\theta\to\infty} \lambda_2^* = 1/2$, see Appendix B). Therefore, we immediately know that the consumer's surplus differential, $S_H - S_F$, is also close to zero, otherwise $V_{2H} - V_{2F} = 0$ fails to hold.

On the other hand, the wage differentials of workers in industry 1 and 3, $w_{iH}^* - w_{iF}^*$ $(i = 1, 3)$, completely depend on the competition effects in $\boldsymbol{\lambda}^*$, since their market-access effects on firms become zero by equalizing the populations. It is evidently that the competition effect on industry 1 is negative and that on industry 3 is positive.

Therefore, for a sufficiently large θ, the utility differentials of workers in industry 1 and 3 completely depend on the competition effects in $\boldsymbol{\lambda}^*$. Since both industry 1 and 3 prefer a less competitive region, the equilibrium $\boldsymbol{\lambda}^*$ becomes unstable.

Why does decreasing τ make the specialization stable?

From (10), the wage differential of workers in industry 2, $w_{2H}^* - w_{2F}^*$, is expressed as follows:

$$w_{2H}^* - w_{2F}^* = \frac{b\overline{L}}{2b-c} F_2(\tau) \left(\lambda_2^* - \frac{1}{2}\right) - \frac{bcK\overline{L}\omega_2^2\tau^2}{2(2b-c)} \left(\lambda_2^* - \frac{1}{2}\right).$$

Thus, for a sufficiently small τ, the market-access effect on firms dominates the competition effect, since the former includes the 1-order term of τ in $F_2(\tau)$. Since λ_2^* converges to $1/2$ *from above*, the market-access effect on firms ($\fallingdotseq$ the wage differential) is positive. Therefore, we immediately obtain that the consumer's surplus differential, $S_H - S_F$, is negative, otherwise $V_{2H} - V_{2F} = 0$ fails to hold.

Next, consider the wage differentials, $w_{iH}^* - w_{iF}^*$ $(i = 1, 3)$. The market-access effects on firms are positive again and are stronger for industries with higher transport costs (see Section 3). Therefore, for a sufficiently small τ, the effect on industry 1 is larger than $-(S_H - S_F)$, which is close enough to the market-access effects on industry 2, and the effect on industry 3 is smaller than $-(S_H - S_F)$. Thus the sum of the all effects except for the competition effect

[7] Rigorous proofs are shown in Appendix B and D.

on industry 1 (resp. 3) is positive (resp. negative). In fact, the effects on industry 1 and 3 are approximately

$$\frac{36a^2b^3L(\omega_1-\omega_2)(\omega_1-\omega_3)\tau^2}{(2b-c)^3\theta}>0,\ -\frac{36a^2b^3L(\omega_2-\omega_3)(\omega_1-\omega_3)\tau^2}{(2b-c)^3\theta}<0, \tag{12}$$

respectively. We should note that they are negligible for a sufficiently large θ, which is consistent with the above case of increasing θ. On the other hand, the competition effect is evidently negative for industry 1 and positive for industry 3. Thus, for both industries, if the competition effects do not exceed the levels of (12) in absolute values, it is better for industry 1 (resp. 3) to locate in region H (resp. F), i.e., $\boldsymbol{\lambda}^*$ becomes stable.[8] The competition effects on industry 1 and 3 are

$$-\frac{9bcL\omega_1^2\tau^2}{4(2b-c)},\ \frac{9bcL\omega_3^2\tau^2}{4(2b-c)},$$

which are independent with θ. Therefore, if θ is small enough, $\boldsymbol{\lambda}^*$ becomes stable.

To summarize, for a sufficiently small τ, region F is preferable in terms of consumer's surplus and region H is preferable in terms of market-access effects on firms for both industry 1 and 3 in $\boldsymbol{\lambda}^*$. To sum up these effects, region H is preferable for industry 1 and region F is preferable for industry 3. If θ is small enough, it is true, i.e., $\boldsymbol{\lambda}^*$ becomes stable, even if the competition effects are considered.

The preceding arguments are for the case of small τ and/or large θ. Now we turn to general case, and see when all industries agglomerate in one region. Let

$$\begin{aligned}\widetilde{\theta} &\equiv \frac{B_3^2-(B_3-2A_3\tau_{trade})^2}{A_3},\\ \widetilde{\tau} &\equiv \frac{B_3-\sqrt{B_3^2-A_3\theta}}{2A_3},\end{aligned}$$

where A_3 and B_3 are defined in Appendix E. We know $\widetilde{\theta}$ and $\widetilde{\tau}$ are both positive and $\widetilde{\tau}<\tau_{trade}$, and obtain the following proposition:

Proposition 3 *If $\theta<\widetilde{\theta}$, then $\boldsymbol{\lambda}^*=(1,1,1)$ is a stable equilibrium iff $\tau\in(\widetilde{\tau},\tau_{trade})$.*

Proof. See Appendix E. ■

By Proposition 1 and 3, we can identify evolution patterns that go "from full agglomeration to regional specialization" with decreasing transport costs. Such evolution patterns might describe the changes of industrial location in Japan during the past four decades.

[8] The condition, $\frac{\partial[V_{2H}(\boldsymbol{\lambda}^*)-V_{2F}(\boldsymbol{\lambda}^*)]}{\partial\lambda_2}\leq 0$, is also required, but it is satisfied for a sufficiently small τ (see Appendix B).

5 Numerical simulations

To present a whole evolution process, we now turn to do some numerical simulations. The parameters are specified as follows:

$$L = 1,\ a = 10,\ b = 15,\ c = 4,\ \rho = 0.$$

About ω_i $(i = 1, 2, 3)$, we set values in three ways:

$$\begin{aligned}
\text{case 1} &\ :\ (\omega_1, \omega_2, \omega_3) = (14.0, 11.0, 8.0),\\
\text{case 2} &\ :\ (\omega_1, \omega_2, \omega_3) = (15.5, 11.0, 6.5),\\
\text{case 3} &\ :\ (\omega_1, \omega_2, \omega_3) = (17.0, 11.0, 5.0).
\end{aligned}$$

Each case has the same mean, i.e., $\omega_2 = 11.0$, but the variances are different from each other. Case 1, 2, and 3 has the smallest, middle, and the largest variance, respectively.

The results are shown in Figure 3, where the horizontal and vertical axes indicate the levels of τ and θ, respectively, and $0 < \lambda_1^* < 1$, $0 < \lambda_2^* < 1$, and $0 < \lambda_3^* < 1$.

We have several remarks about Figure 3. First, there are no multiple equilibria in all cases, i.e., any pair (τ, θ) corresponds to one stable equilibrium. Second, in all cases, the full agglomeration pattern is stable in the lower right-hand area that is consistent with Proposition 3, while the full dispersion pattern is stable in the upper area that is consistent with Proposition 2. Between these two areas, various asymmetric location patterns, including complete or partial regional specialization, could be stable. Third, with increasing the variance of ω, the "asymmetric location pattern" area expands, while the "full agglomeration pattern" area shrinks. In general, with $(\omega_1 + \omega_2 + \omega_3)$ and ω_2 being constant, we have

$$\frac{\partial \overline{\theta}_0}{\partial \omega_1} > 0,\ \frac{\partial \overline{\theta}_1}{\partial \omega_1} > 0,\ \frac{\partial \overline{\theta}_2}{\partial \omega_1} > 0,\ \frac{\partial \widetilde{\theta}}{\partial \omega_1} < 0,$$

by simple calculation[9]. It is natural that more asymmetry in parameters (ω) gives more asymmetry in location patterns. If asymmetry in ω vanishes (i.e., one industry case), the "asymmetric location pattern" area also vanishes and the possibly stable location patterns are limited to the full agglomeration and the full dispersion.

Finally, we find that decreasing τ or increasing θ tends to make industries with lower transport costs disperse in almost all the area in each case. For example, in case 1, decreasing τ with $\theta = 10$ brings such a location-transition path as $(1, 1, 1) \to (1, 1, \lambda_3^*) \to (1, 1, 0) \to (1, \lambda_2^*, 0)$,

[9]In fact, case 1 corresponds to a case with $\min\{\overline{\theta}_1, \overline{\theta}_2\} < \overline{\theta}_0 < \widetilde{\theta}$, in which the full agglomeration can be changed to complete or partial specialization, or the full dispersion by decreasing τ with θ being constant. On the other hand, case 2 corresponds to a case with $\min\{\overline{\theta}_1, \overline{\theta}_2\} < \widetilde{\theta} < \overline{\theta}_0$, in which the full agglomeration can not be changed to the full dispersion, and case 3 corresponds to a case with $\widetilde{\theta} < \min\{\overline{\theta}_1, \overline{\theta}_2\} < \overline{\theta}_0$, in which the full agglomeration must be changed to complete specialization by decreasing τ with θ being constant. It should be noted that $\min\{\overline{\theta}_1, \overline{\theta}_2\} < \overline{\theta}_0$ always holds (see Appendix C).

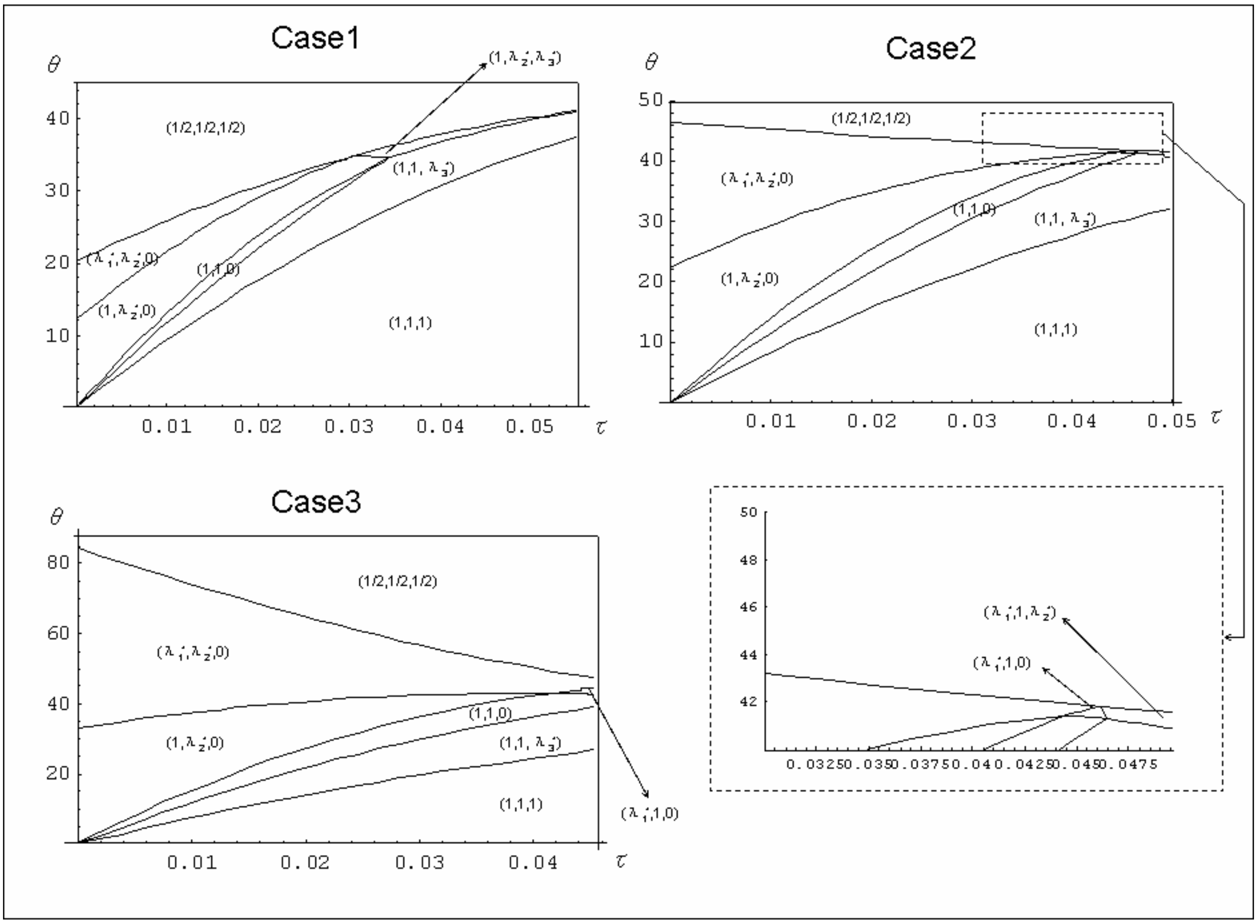

Figure 3: Simulation results 1

and increasing θ with $\tau = 0.04$ brings such a location-transition path as $(1, 1, 1) \to (1, 1, \lambda_3^*) \to (1, \lambda_2^*, \lambda_3^*) \to (1/2, 1/2, 1/2)$. These equilibria are consistent with intuition in the sense that industries with higher transport costs can reduce more costs by locating in the bigger market. However, there are some exceptions, e.g., $(\lambda_1^*, 1, \lambda_3^*)$ and $(\lambda_1^*, 1, 0)$ in case 2, and $(\lambda_1^*, 1, 0)$ in case 3. The reasons of their occurrence will be discussed later.

In the next simulations, we focus on specifying the share of workers of each industry residing in H, i.e., λ_i^* $(i = 1, 2, 3)$, by decreasing τ and letting θ constant in each case. Some of the results are shown in Figure 4 (case 1) and Figure 5 (case 2 and case 3), where the horizontal axes indicate the levels of τ and the vertical axes indicate λ_i^* $(i = 1, 2, 3)$ (left-side graphs) or $\sum_{i=1}^{3} \lambda_i^*$ (right-side graphs).

In Figure 4, we set four different values of θ, 40, 30, 20, and 10. The case of (ii), (iii), and (iv) correspond to "*from full agglomeration to full dispersion*", "*from full agglomeration to partial specialization*", and "*from full agglomeration to complete specialization*," respectively. On the other hand, the case of (i) starts from "partial agglomeration" and quickly changes to the full dispersion because of high urban costs. In spite of such differences, decreasing τ lets industries with lower transport costs disperse in all cases. As a result, industries having higher transport costs never occupy a lower share in the bigger region (H) than those with lower transport costs. In addition, the share of workers of all industries residing in H, i.e., $\sum_{i=1}^{3} \lambda_i^*$, is monotone decreasing (with a jump in some cases) and converges to 1.5 (half of the total workers) by reducing τ in all cases.

However, Figure 5 shows other types of location patterns: industries with higher transport costs can occupy lower shares in the bigger region than those with lower transport costs, e.g., $(\lambda_1^*, 1, \lambda_3^*)$, $(\lambda_1^*, 1, 0)$ in (i), and $(\lambda_1^*, \lambda_2^*, 0)$ in (ii), where $\lambda_1^* < \lambda_2^*$. Such counter-intuitive patterns can be reasoned by the competition effect discussed in Section 3.

Wage differentials are expressed by "market-access effect on firms + competition effect" as (10). In addition, (10) shows that the market-access effect on firms works more strongly for industries with higher transport costs (see Section 3). Therefore, if the competition effect does not exist, we always have $w_{1H}^* - w_{1F}^* > w_{2H}^* - w_{2F}^* > w_{3H}^* - w_{3F}^*$, which implies that industries with higher transport costs have stronger incentives to locate in the the bigger region (H). However, this is not true if the competition effect exists. Equation (10) also shows that the competition effect works more strongly for industries with higher transport costs (see Section 3). Therefore, if too many firms in an industry with a higher transport cost agglomerate, then the competition effect becomes large, which decreases the incentives for the firms of higher transport costs to locate in H.

For example, consider location patterns $(1, 1, 1)$ and $(1, 1, 0)$. By (10), we always have $w_{1H}^* - w_{1F}^* > w_{2H}^* - w_{2F}^* > w_{3H}^* - w_{3F}^*$ for $\tau \in (0, \tau_{trade})$ in the case of $(1, 1, 1)$, even if we consider

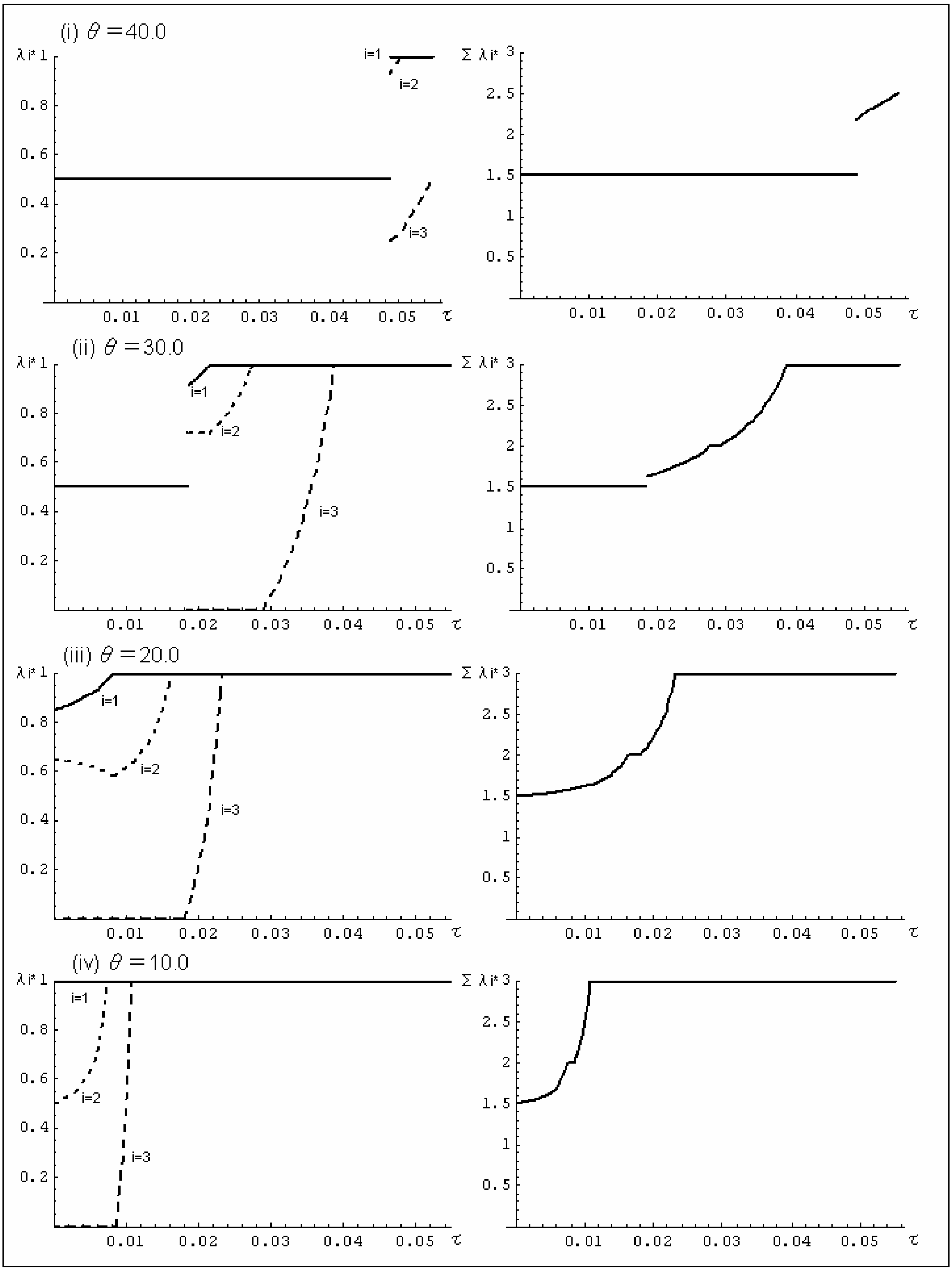

Figure 4: Simulation results 2: case 1 (left: λ_i^* $(i = 1, 2, 3)$, right: $\sum_{i=1}^{3} \lambda_i^*$)

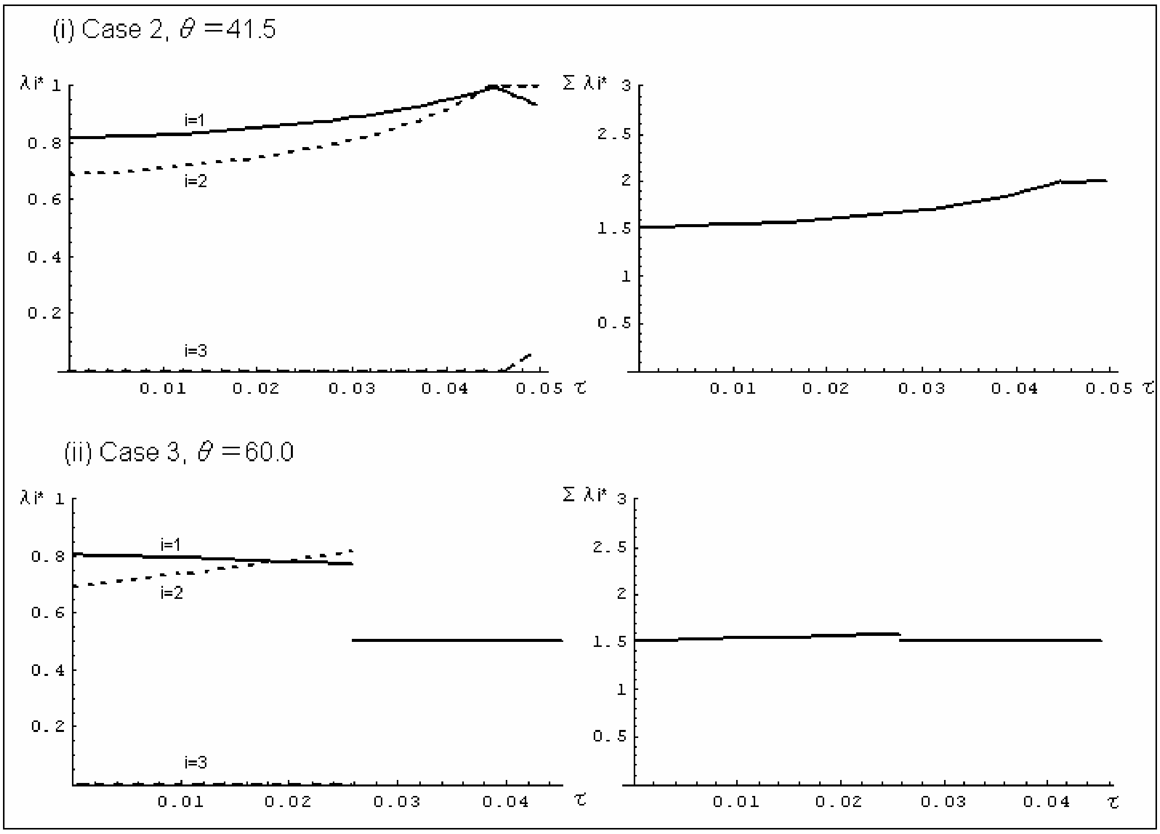

Figure 5: Simulation results 3 (left: λ_i^* $(i = 1, 2, 3)$, right: $\sum{}_{i=1}^{3}\lambda_i^*$)

the competition effects. Thus, industries with higher transport costs have stronger incentives to locate in H, so in any cases we must find such transition as $(1,1,1) \to (1,1,\lambda_3^*)$, i.e., industry 3 starts to relocate to the other region by decreasing τ or increasing θ (see all cases in Figure 3). But in the case of $(1,1,0)$, the market-access effect shrinks to one third of that in the case of $(1,1,1)$, and as a result, $w_{1H}^* - w_{1F}^* < w_{2H}^* - w_{2F}^*$ might hold when τ is large. In this situation, firms of industry 2 have a stronger incentive to locate in H than that of industry 1, thus industry 1 could leave H earlier than industry 2 when τ decreases and/or θ increases. This is the reason why we find such transition as $(1,1,0) \to (\lambda_1^*,1,0)$ in case 2 or case 3 in Figure 3.

This result is very contrastive to Zeng (2005). Zeng (2005) assumed asymmetry in required number of immobile unskilled workers instead of transport costs and analyze location patterns of multiple industries. As a result, he showed that industries requiring less unskilled workers must not occupy lower shares in the region with higher wage of unskilled workers than those requiring more unskilled workers (Theorem 1). His result may be understood as follows. In his model, wage (= profit) differentials are expressed by

$$\text{market-access effect on firms} + \text{competition effect} + \text{wage saving in unskilled workers}.$$

The first two terms are always identical for all industries which have the same location pattern because of the symmetry in transport costs. Thus, for such industries, wage differentials are originated from only the wage saving in unskilled workers. Let region H be the one with higher wage of unskilled workers and let industry 1 (resp. 2) be the one requiring less (resp. more) unskilled workers. Then, by the above discussion, we always have $w_{1H}^* - w_{1F}^* > w_{2H}^* - w_{2F}^*$ when the two industries have the same location pattern. Therefore, industry 1 (resp. 2) has a stronger incentive to locate in H (resp. F) than industry 2 (resp. 1), which derives $\lambda_1^* \geq \lambda_2^*$.

6 Concluding remarks

Regional specialization via differences in transport costs has been observed in Japanese manufacturing industries. This paper tried to provide a theoretical foundation for this phenomenon by investigating where various industries tend to locate when the transportation technology develops. To this aim, we have analyzed the location of industries that are differentiated by their transport costs by use of an analytically solvable model of new economic geography. Effects of urban costs are also included in the model. The obtained results are consistent with the observed empirical phenomenon.

The real world is more complicated than our established model, of course. For example, about 80% of software and information processing industries, which are typical ones with low transport costs, have remained in the core until now. To explain this fact, we have to introduce the other agglomeration force in such industries, i.e., inter-firm communication externality. Nevertheless, we believe that our model is useful for understanding some aspects of the real economy.

Appendix A. Proof of Proposition 1 (i)

See the complete version of the paper, which is downloadable at http://www.ec.kagawa-u.ac.jp/~htakatsu/

Appendix B. Proof of Proposition 1 (iv)

See the complete version of the paper, which is downloadable at http://www.ec.kagawa-u.ac.jp/~htakatsu/

Appendix C. Proof of Proposition 1 (ii) and (iii)

See the complete version of the paper, which is downloadable at http://www.ec.kagawa-u.ac.jp/~htakatsu/

Appendix D. Proof of Proposition 2

(Stability of the full dispersion equilibrium) The only interior equilibrium is evidently $\boldsymbol{\lambda}^* = (1/2, 1/2, 1/2)$. Let $\Delta \equiv (\delta_{ij})_{3\times 3}$ and its characteristic equation be $t^3 + At^2 + Bt + C = 0$; then, a necessary and sufficient stability condition of $\boldsymbol{\lambda}^*$ is given by

$$
\begin{aligned}
&A < 0 \Leftrightarrow Tr(\Delta) > 0 \\
&\quad \Leftrightarrow \frac{3}{2}\theta + \frac{6ab(b-c)(\omega_1+\omega_2+\omega_3)}{(2b-c)^2}\tau + \frac{3b(6b^2-2bc-c^2)(\omega_1^2+\omega_2^2+\omega_3^2)}{2(2b-c)^2}\tau^2 > 0, \\
&C < 0 \Leftrightarrow |\Delta| > 0 \\
&\quad \Leftrightarrow \frac{81b^2c^2}{8(2b-c)^2}(\omega_1^2\omega_2^2+\omega_2^2\omega_3^2+\omega_3^2\omega_1^2)\tau^4\theta + C1 > 0, \\
&AB < C \Leftrightarrow Tr(\Delta)(\delta_{11}\delta_{22}+\delta_{22}\delta_{33}+\delta_{33}\delta_{11}-\delta_{12}\delta_{21}-\delta_{23}\delta_{32}-\delta_{31}\delta_{13}) > |\Delta| \\
&\quad \Leftrightarrow \frac{27bc}{4(2b-c)}(\omega_1^2+\omega_2^2+\omega_3^2)\tau^2\theta^2 + C2\theta + C3 > 0
\end{aligned}
$$

(Samuelson, 1945, p.432), where $C1$, $C2$, and $C3$ are all independent with θ. For a sufficiently large θ, the above inequalities are determined by the first terms, therefore, they are evidently true. ■

(Unstability of complete specialization equilibria) If $\boldsymbol{\lambda}^* = (1, \lambda_2^*, 0)$ is a stable equilibrium, we obtain

$$
\begin{aligned}
&V_{1H}(\boldsymbol{\lambda}^*) - V_{1F}(\boldsymbol{\lambda}^*) \geq 0, \\
&V_{3H}(\boldsymbol{\lambda}^*) - V_{3F}(\boldsymbol{\lambda}^*) \leq 0.
\end{aligned}
$$

Using $V_{2H}(\boldsymbol{\lambda}^*) - V_{2F}(\boldsymbol{\lambda}^*) = 0$, these imply

$$
\frac{-9bcL(2b-c)^2\omega_1^2\tau^2\theta + C1}{4(2b-c)^3\theta - 48ab(6b^2-5bc+c^2)\omega_2\tau + 12b(12b^3-10b^2c+c^3)\omega_2^2\tau^2} \geq 0,
$$

$$\frac{9bcL(2b-c)^2\omega_3^2\tau^2\theta + C2}{4(2b-c)^3\theta - 48ab(6b^2-5bc+c^2)\omega_2\tau + 12b(12b^3-10b^2c+c^3)\omega_2^2\tau^2} \leq 0,$$

respectively, where $C1$ and $C2$ are both independent with θ. For a sufficiently large θ, these inequalities are not satisfied. The other cases, $(1, 0, \lambda_3^*)$ and $(\lambda_1^*, 1, 0)$, can be also showed to be unstable. ■

(Unstability of partial specialization equilibria) Assume that the equilibrium $\boldsymbol{\lambda}^* = (1, \lambda_2^*, \lambda_3^*)$ with $\lambda_2^* \in (0,1)$, $\lambda_3^* \in (0,1)$ is stable. Then, we have $V_{2H}(\boldsymbol{\lambda}^*) - V_{2F}(\boldsymbol{\lambda}^*) = 0$, $V_{3H}(\boldsymbol{\lambda}^*) - V_{3F}(\boldsymbol{\lambda}^*) = 0$, and

$$\begin{aligned} & V_{1H}(\boldsymbol{\lambda}^*) - V_{1F}(\boldsymbol{\lambda}^*) \geq 0 \\ \Leftrightarrow \; & \frac{-9bc^2L(2b-c)^2(\omega_1^2\omega_2^2 + \omega_2^2\omega_3^2 + \omega_3^2\omega_1^2)\tau^2\theta + C1}{4c(2b-c)^3(\omega_2^2+\omega_3^2)\theta + C2} \geq 0, \end{aligned}$$

where $C1$ and $C2$ are both independent with θ. For a sufficiently large θ, this inequality is not satisfied. The other cases, $(\lambda_1^*, 1, \lambda_3^*)$ and $(\lambda_1^*, \lambda_2^*, 0)$, can be also showed to be unstable. ■

Appendix E. Proof of Proposition 3

When $\boldsymbol{\lambda}^* = (1,1,1)$, the utility differential of industry i $(= 1, 2, 3)$ is rewritten as

$$V_{iH}(\boldsymbol{\lambda}^*) - V_{iF}(\boldsymbol{\lambda}^*) = \left[-A_i\tau^2 + B_i\tau - \frac{\theta}{4}\right]\overline{L},$$

where

$$\begin{aligned} A_i \equiv & \frac{b}{4(2b-c)^2}\left[\left(12\omega_i^2 + 2\sum_{j=1}^{K}\omega_j^2\right)b(b-c) + 3c^2\omega_i^2\right] > 0, \\ B_i \equiv & \frac{ab}{(2b-c)^2}\left[3(2b-c)\omega_i + b\sum_{j=1}^{K}\omega_j\right] > 0. \end{aligned}$$

Thus, we have

$$\begin{aligned} & \{V_{1H}(\boldsymbol{\lambda}^*) - V_{1F}(\boldsymbol{\lambda}^*)\} - \{V_{3H}(\boldsymbol{\lambda}^*) - V_{3F}(\boldsymbol{\lambda}^*)\} \\ & \qquad = \frac{9bL(\omega_1-\omega_3)\{4a - (2b-c)(\omega_1+\omega_3)\tau\}\tau}{4(2b-c)} > 0, \qquad (13) \\ & \{V_{2H}(\boldsymbol{\lambda}^*) - V_{2F}(\boldsymbol{\lambda}^*)\} - \{V_{3H}(\boldsymbol{\lambda}^*) - V_{3F}(\boldsymbol{\lambda}^*)\} \\ & \qquad = \frac{9bL(\omega_2-\omega_3)\{4a - (2b-c)(\omega_2+\omega_3)\tau\}\tau}{4(2b-c)} > 0, \qquad (14) \end{aligned}$$

where the inequalities are from

$$\begin{aligned} \frac{4a}{(2b-c)(\omega_1+\omega_3)} - \tau_{trade} &= \frac{2a(\omega_1-\omega_3)}{(2b-c)\omega_1(\omega_1+\omega_3)} > 0, \\ \frac{4a}{(2b-c)(\omega_2+\omega_3)} - \tau_{trade} &= \frac{2a(2\omega_1-\omega_2-\omega_3)}{(2b-c)\omega_1(\omega_2+\omega_3)} > 0. \end{aligned}$$

Inequalities (13) and (14) imply that, if $V_{3H}(\boldsymbol{\lambda}^*) - V_{3F}(\boldsymbol{\lambda}^*) > 0$, then $V_{1H}(\boldsymbol{\lambda}^*) - V_{1F}(\boldsymbol{\lambda}^*) > 0$ and $V_{2H}(\boldsymbol{\lambda}^*) - V_{2F}(\boldsymbol{\lambda}^*) > 0$, so that $\boldsymbol{\lambda}^* = (1,1,1)$ is a stable equilibrium. On the other hand, we have

$$\left.\frac{\partial(V_{3H}(\boldsymbol{\lambda}^*) - V_{3F}(\boldsymbol{\lambda}^*))}{\partial\tau}\right|_{\tau=\tau_{trade}} > 0$$

by a simple calculation. Let

$$\widetilde{\tau} = \frac{B_3 - \sqrt{B_3^2 - A_3\theta}}{2A_3}$$

be the smaller solution of $V_{3H}(\boldsymbol{\lambda}^*) - V_{3F}(\boldsymbol{\lambda}^*) = 0$. If $\widetilde{\tau} < \tau_{trade}$, then $\boldsymbol{\lambda}^* = (1,1,1)$ is a stable equilibrium for $\tau \in (\widetilde{\tau}, \tau_{trade})$. Finally, noting that

$$\widetilde{\tau} < \tau_{trade} \Leftrightarrow \theta < \widetilde{\theta} \equiv \frac{B_3^2 - (B_3 - 2A_3\tau_{trade})^2}{A_3},$$

the proof is completed.■

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