Locating manufacturing and distribution centers: An integrated supply chain-based spatial interaction approach

Jiuh-Biing Sheu [*]

Institute of Traffic and Transportation, National Chiao Tung University, 4F, 114 Chung Hsiao W. Rd., Sec. 1, Taipei 10012, Taiwan, ROC

Abstract

This study investigates the facility location problem of transnational personal computer (PC) manufacturing for the domestic market of China. An integrated supply chain-based spatial interaction model is formulated to determine facility locations of the transnational PC manufacturing centers and regional product distribution centers in China, with the goal of maximizing the potential rate of return on facility investment. The numerical results show that the Shanghai municipality is ranked highest for siting both the manufacturing and distribution centers for a transnational PC manufacturing enterprise.
© 2003 Elsevier Ltd. All rights reserved.

Keywords: Supply chain; Spatial interaction; Transnational personal computer manufacturing; Transnational operations

1. Introduction

Mainland China has the potential to dominate the personal computer (PC) market in the Asia-Pacific area. With the rapid growth of PC demand in China, the domestic PC market in China has surpassed Germany's, becoming the third largest in the world. According to related statistics (Chen, 2001), the annual national PC demand of China exceeded seven million units in 2001, a growth of 12.7% over 2000. Furthermore, such growth may be further stimulated in the future given that China became a formal member of the World Trade Organization (WTO) in 2001. With economic globalization, overseas PC manufacturers, relying mainly on transnational

[*] Tel.: +886-2-2349-4963; fax: +886-2-2349-4953.
E-mail address: jbsheu@mail.nctu.edu.tw (J.-B. Sheu).

operational strategies to satisfy the growing demands from their world-wide customers, may grasp this opportunity to enhance their international business competitiveness worldwide.

Nevertheless, the facility location problem in China is critical to transnational PC manufacturing enterprises for the following reasons. First, uncertainties in logistical factors, e.g., inter-province shipment risks and costs, the diversity of local governmental regulations in logistics, and complexity of the market are still significant factors in China. In addition, external factors such as different exchange rates, trade barriers, transfer prices, labor resources, and cultural differences and consumer behavior should also be considered in the transnational operational scenario. As described by Bowersox and Closs (1996a), the globalization of logistics activities is driven mainly by five forces: (1) deregulation, (2) supply chain perspective, (3) economic growth, (4) regionalization, and (5) technology, and thus increasing the complexity of transnational business operations. Accordingly, transnational PC manufacturing enterprises must rely on sophisticated inbound and outbound logistics management strategies in response to corresponding business operating challenges in China. In this situation, the facility network design problem plays a key role in determining the performance of logistics systems. Supporting arguments can also be found elsewhere (Bowersox and Closs, 1996b).

Research on facility location models has mainly dealt with assigning facilities to serve their nearest demand areas, in order to minimize aggregate operational costs (Hakimi, 1964; Cornuejols et al., 1977; Neebe and Rao, 1983; Klincewicz and Luss, 1986; Mirchandani and Francis, 1990; Daskin, 1995; Pirkul and Jayaraman, 1996; Bramel and Simchi-Levi, 1997). To achieve this goal, appropriate decisions in terms of the number and location of facilities as well as the demand area potentially served by each facility, should be made using the facility allocation logic rules. Herein, the properties of the spatially interactive travel behavior have been increasingly incorporated in formulating facility location problems to make these models more suitable for practical applications (Wilson, 1969; Coelho and Wilson, 1976; Leonardi, 1978; Beaumont, 1980; Erlenkotter and Leonardi, 1985; Jacobsen, 1986; Holmberg, 1996).

One typical example is use of the spatial gravity model, which characterizes the strength of spatial interaction between each pair of nodes in an activity-corresponding network. In Leonardi's study (1983), random utility theories are used to formulate the resulting models as nonlinear integer programming models with the entropy-maximizing objective. It addition, a variety of techniques, including dynamic programming models (Campbell, 1990; Drezner and Wesolowsky, 1991; Bean et al., 1992; Webster and Gupta, 1995) and heuristic algorithms (Friesz et al., 1988; Miller et al., 1992), have been utilized to increase the efficiency in searching for a final solution. One distinctive feature of these advanced methods is that demand-related attributes, e.g., demand patterns and demand growth rates, are treated in either the dynamic or the stochastic extent rather than in the static domain as in traditional approaches (Drezner and Wesolowsky, 1980; Daganzo, 1987, 1988; Erlenkotter, 1989; Ghosh and Craig, 1991; Hakimi and Kou, 1991).

In view of limited in-depth investigations in the aforementioned subject in the literature, here we propose an integrated supply-chain based spatial interaction model to formulate the overseas facility network design problem, considering the Chinese PC domestic market. In addition to utilizing the fundamentals of spatial interaction approaches, the concept of supply chain management (SCM) is employed, where corresponding facilities including manufacturing and distribution centers are considered. In formulating the proposed model, we also consider the nation-wide multi-member inbound and outbound logistics-related factors, e.g., material source

accessibility, transportation and inventory costs, potential benefits, inter-province distribution restrictions, and long-term regional market conditions to alleviate the decision bias for locating the corresponding facilities.

2. Model

The proposed model incorporates the concept of logistical distribution channels of the PC supply chain into a comprehensive spatial interaction framework. Herein, a simple three-layer PC supply chain is specified, as shown in Fig. 1, which groups traditional PC supply chain members into three major layers: (1) supply, (2) manufacturing and (3) demand, representing functions of supplying PC assembling materials, manufacturing, and product demand, respectively. According to previous tasks on regional market analyses, given regions, referring to chain members of the specified PC supply chain, can be selected as candidates for facility location, and then are
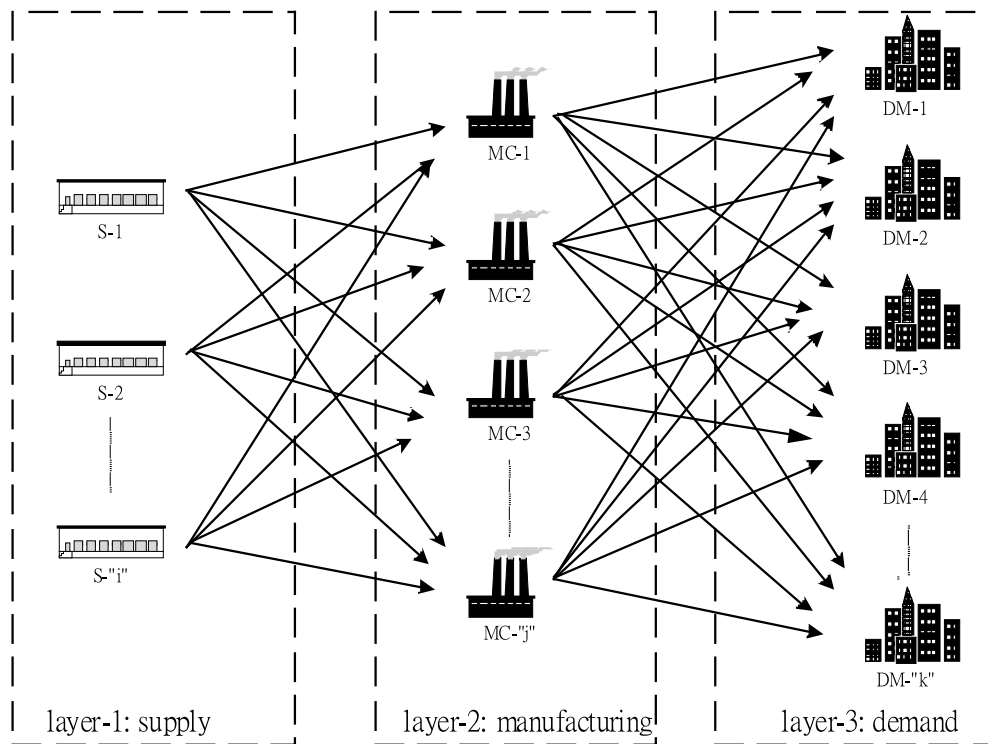
S: supplier of assembling materials

MC: manufacturing center

DM: demand market

Fig. 1. Framework of the specified spatial interaction relationships of PC distribution channels.

assigned to corresponding layers. Using the proposed spatial interaction model, the nation-wide multi-layer physical flows of the PC supply chain, referring to state variables of the proposed framework, are estimated. Then these estimated state variables are used as the basis to finalize the decision of locating corresponding manufacturing and distribution centers in the layers of manufacturing and demand, respectively.

There are two types of state variables:

(1) $x_{i,j}$ represents the amount of potential physical distribution flow between a given pair of the PC chain members i and j in the layers of supply and manufacturing.
(2) $x_{j,k}$ indicates the amount of potential physical distribution flow between a given pair of the PC chain members j and k in the layers of manufacturing and demand.

It is noteworthy that the specified state variables serve to characterize the strength of the spatial interaction in the PC supply chain framework. In contrast with the decision variables, which are controllable in mathematical programming models, these state variables are not controllable by transnational PC manufacturing enterprises in the overseas facility network planning scenario. This may also explain why the use of mathematical programming methods is not considered in this study. In addition, some pioneering researchers (Tong and Walter, 1980; Schemmer, 1982; Allen, 1991) may have raised issues in terms of the effects of qualitative factors, e.g., restrictions and incentives of overseas governmental regulations, labor availability, and accessibility of transportation facilities, on the corresponding decision-making process. In reality, these uncertainties can be regarded as the corresponding effects on the degree of spatial interaction between given dyad geographical regions, and thus be readily incorporated into the proposed model. Herein, they are treated as factors influencing spatial interaction frictions in the proposed model, and quantified by parameters associated with corresponding spatial interaction cost functions.

The model assumes:

(1) The spatial interaction strength between any given pair of chain members in two different layers changes proportionally with the physical amounts associated with the chain members.
(2) The regional long-term supply and demand amounts, referring to annual physical quantities originating from each given region of PC assembling-material supply and demanded by each given regional demand market, respectively, are known. [1]
(3) The spatial interaction friction function is a negative exponential function with respect to the logistics and manufacturing costs. [2]

---

[1] This assumption also implies that the proposed model is affected mainly by the long-term market changes rather than the short-term market changes in the facility network decision-making process. Correspondingly, the short-term changes of market conditions are supposed not to have a profound impact on the corresponding decision-making problem in this study. In reality, such a postulation is consistent with the results of our preliminary analyses conducted elsewhere (Lee, 2002).

[2] This postulation exhibits the property that the spatial interaction strength decreases following a negative exponential form, whereas the corresponding friction effect increases. Similar treatments can also be found elsewhere (Wilson, 1969).

The generalized form of the proposed model is presented as (see Appendix A for variable and parameter definitions):

$$\mathbf{X}_{(I\cdot J+J\cdot K)\times 1} = \mathbf{F}\lfloor x_i, x_j^{\alpha_j}, x_k^{\alpha_k}, C\rfloor_{(I\cdot J+J\cdot K)\times 1} \tag{1}$$

The two vectors $\mathbf{X}_{(I\cdot J+J\cdot K)\times 1}$ and $\mathbf{F}\lfloor x_i, x_j^{\alpha_j}, x_k^{\alpha_k}, C\rfloor_{(I\cdot J+J\cdot K)\times 1}$ both have the same dimensions $((I\cdot J + J\cdot K)\times 1)$, and can be further expressed as

$$\mathbf{X}_{(I\cdot J+J\cdot K)\times 1} = \begin{bmatrix} \mathbf{X}_{i,j} \\ \mathbf{X}_{j,k} \end{bmatrix}_{(I\cdot J+J\cdot K)\times 1} \tag{2}$$

where

$$\mathbf{X}_{i,j} = [x_{i,j}, \quad i = 1, 2, \ldots, I; \ j = 1, 2, \ldots, J]^{\mathbf{T}} \tag{3}$$

$$\mathbf{X}_{j,k} = [x_{j,k}, \quad j = 1, 2, \ldots, J; \ k = 1, 2, \ldots, K]^{\mathbf{T}} \tag{4}$$

$$\mathbf{F}[x_i, x_j^{\alpha_j}, x_k^{\alpha_k}, C]_{(I\cdot J+J\cdot K)\times 1} = \begin{bmatrix} \mathbf{F}_{i,j} \\ \mathbf{F}_{j,k} \end{bmatrix}_{(I\cdot J+J\cdot K)\times 1} \tag{5}$$

where

$$\mathbf{F}_{i,j} = \lfloor f_{x_{i,j}}, \quad i = 1, 2, \ldots, I; \ j = 1, 2, \ldots, J\rfloor^{\mathbf{T}} \tag{6}$$

$$\mathbf{F}_{j,k} = \lfloor f_{x_{j,k}}, \quad j = 1, 2, \ldots, J; \ k = 1, 2, \ldots, K\rfloor^{\mathbf{T}} \tag{7}$$

Both the disaggregate spatial interaction functions, $f_{x_{i,j}}$ and $f_{x_{j,k}}$ are given respectively by

$$f_{x_{i,j}} = \frac{x_i \times x_j^{\alpha_j} \times C_{i,j}}{\sum_{\forall j'} x_{j'}^{\alpha} \times C_{i,j'}} \tag{8}$$

$$f_{x_{j,k}} = \frac{x_j^{\alpha_j} \times x_k^{\alpha_k} \times C_{j,k}}{\sum_{\forall j'} x_{j'}^{\alpha} \times C_{j',k}} \tag{9}$$

According to Assumption 3, both $C_{i,j}$ and $C_{j,k}$ are formulated with specific exponential forms with respect to the corresponding unit costs of manufacturing and logistics. These unit costs include four main items: (1) costs of assembling-material procurement (c_*^a), (2) transportation costs (c_*^t), (3) storage/inventory costs (c_*^s), and (4) manufacturing costs (c_*^m). Therefore, $C_{i,j}$ and $C_{j,k}$ are expressed as follows.

$$C_{i,j} = \exp\lfloor -\beta_i \times c_i^a - \beta_{i,j} \times c_{i,j}^t - \beta_j \times c_j^m\rfloor \tag{10}$$

$$C_{j,k} = \exp\lfloor -\beta_j \times c_j^s - \beta_{j,k} \times c_{j,k}^t - \beta_k \times c_k^s\rfloor \tag{11}$$

In addition, it is worth mentioning that some external factors such as different labor resources, unknown facility investment risks, political uncertainties, and inconsistency in local governments' laws and regulations for corresponding manufacturing and logistics activities may exist in China. However, these factors are quite difficult to incorporate in other mathematical models, such as mixed integer programming models, which are extensively used for the strategic design of domestic supply chains. Employing the proposed spatial interaction model, these external factors are aggregated with the forms of the aforementioned parameters using a proposed calibration

procedure. As described later, these parameters can then be used to quantify the corresponding resisting effects in the procedure of determining appropriate facility locations for transnational PC manufacturing in China.

The next stage is to derive the monetary measures used in the final decision-making logic for appropriately locating corresponding facilities in layers M and D of the supply chain-based spatial interaction framework. From the viewpoint of business operations, the quantities of costs and benefits could be more meaningful in the final decision-making process than any other measurements, including the estimated spatial interaction strength. Therefore, employing the concept of utility functions, similar to Wilson (1969), we derive the monetary measures as follows, by transforming these proposed spatial interaction functions. Let the physical amounts of logistical $x_j^{\alpha_j}$ and $x_k^{\alpha_k}$ shown in Eqs. (8) and (9) be two exponential functions with respect to the given PC manufacturer's benefits, u_j and u_k, originating from the physical amounts of assembling materials distributed from chain layers S to M, and from M to D, respectively. [3] Accordingly, the aforementioned postulations can be mathematically expressed as

$$x_j^{\alpha_j} = \exp(b_j \times u_j) \tag{12}$$

$$x_k^{\alpha_k} = \exp(b_k \times u_k) \tag{13}$$

Combine Eqs. (12) and (13) with the corresponding spatial friction functions shown in Eqs. (10) and (11). Then, we have the disaggregated net benefit indexes denoted by $\tilde{\mu}_{i,j}$ and $\tilde{\mu}_{j,k}$, which accompany the physical amounts distributed between the given chain members of i and j, and those of j and k, respectively. Herein, $\tilde{\mu}_{i,j}$ and $\tilde{\mu}_{j,k}$ are given by

$$\tilde{\mu}_{i,j} = u_j - (c_i^{\mathrm{a}} + c_{i,j}^{\mathrm{t}} + c_j^{\mathrm{m}}) = \frac{\alpha_j}{b_j} \ln(x_j) - (c_i^{\mathrm{a}} + c_{i,j}^{\mathrm{t}} + c_j^{\mathrm{m}}) \tag{14}$$

$$\tilde{\mu}_{j,k} = u_k - (c_j^{\mathrm{s}} + c_{j,k}^{\mathrm{t}} + c_k^{\mathrm{s}}) = \frac{\alpha_k}{b_k} \ln(x_k) - (c_j^{\mathrm{s}} + c_{j,k}^{\mathrm{t}} + c_k^{\mathrm{s}}) \tag{15}$$

Accordingly, we specified two monetary measures δ_j and δ_k given respectively by

$$\delta_j = \left(\sum_{\forall i} \tilde{\mu}_{i,j} \times x_{i,j} + \sum_{\forall k} \tilde{\mu}_{j,k} \times x_{j,k} \right) \Big/ 2 \times \sum_{\forall k} x_{j,k} \tag{16}$$

$$\delta_k = \sum_{\forall j} \tilde{\mu}_{j,k} \times x_{j,k} \Big/ \sum_{\forall j} x_{j,k} \tag{17}$$

Using these monetary measures, we propose the following decision-making logic to determine the locations of the corresponding facilities in layers M and D.

Step 0: Initialize system states of an integrated supply chain-based spatial interaction framework. Herein, the potential regions, which may be suitable for allocating corresponding faci-

---

[3] The amounts of both PC assembling materials and products are accompanied with the benefits that may be potentially gained in layer D, and thus can be characterized with the functions of the corresponding benefits u_j and μ_k.

lities, are targeted according to the missions and goals in strategic planning of business operations.

Step 1: Forecast the state vector, i.e., $\mathbf{X}_{(I \cdot J + J \cdot K) \times 1}$, using the proposed integrated supply chain-based spatial interaction model.

Step 2: Calculate the monetary measure associated with each facility candidate (e.g., δ_j and δ_k) employing Eqs. (16) and (17) together with the predicted state variables.

Step 3: Rank these facility location candidates of a given layer in descending order according to the corresponding monetary measures calculated previously. Then determine the appropriate facilities for layers M and D with the following rules:

(1) For layer M:

$$\text{IF} \quad \frac{\delta_j}{\sum_{\forall j \in M} \delta_j} \times \gamma_j > \lambda_M, \quad \text{for all } j \tag{18}$$

THEN the facility associated with the given chain member j of layer M is allocated to the corresponding region

(2) For layer D:

$$\text{IF} \quad \frac{\delta_k}{\sum_{\forall k \in D} \delta_k} \times \gamma_k > \lambda_D, \quad \text{for all } k \tag{19}$$

THEN the facility associated with the given chain member k of layer D is allocated to the corresponding region. [4]

where γ_j and γ_k are given by

$$\gamma_j = \frac{\sum_{\forall k} x_{j,k}}{\sum_{\forall i} x_{i,j}} \tag{20}$$

$$\gamma_k = \frac{\sum_{\forall j} x_{j,k}}{\sum_{\forall j} \sum_{\forall k} x_{j,k}} \tag{21}$$

3. Parameter calibration

This section presents the scenario of calibrating the parameters (i.e., α_* and β_*) shown in the spatial interaction functions using the collected statistical data. The proposed parameter calibration procedure was constructed according to the fundamentals of maximum likelihood estimation approaches, which were extensively utilized in the previous literature (Evans, 1975; Hyman, 1983; Stetzer, 1983). Under the goal, as shown in Eq. (22), the estimation errors in terms of the physical quantities associated with the chain members j and k (i.e., $x_j^{\alpha_j}$ and $x_k^{\alpha_k}$) and the spatial friction functions ($C_{i,j}$ and $C_{j,k}$) are calculated in iteration, and compared with pre-set

---

[4] In real-world applications, the corresponding decision makers of a given transnational PC manufacturer, e.g., the managers of marketing and manufacturing sections, are allowed to determine these two thresholds (i.e., λ_D and λ_M) according to their operational goals.

thresholds. With the help of the Newton–Raphson technique to search for the final solutions, the maximum likelihood estimates of these parameters can be determined once the rule-termination conditions are satisfied.

$$\text{Min}\, z = [\mathbf{X}(x_j^{\alpha_j}, x_k^{\alpha_k}) - \mathbf{X}^{\text{real}}]^{\mathbf{T}}[\mathbf{X}(x_j^{\alpha_j}, x_k^{\alpha_k}) - \mathbf{X}^{\text{real}}] + [\mathbf{C}(C_{i,j}, C_{j,k}) - \mathbf{C}^{\text{real}}]^{\mathbf{T}}[\mathbf{C}(C_{i,j}, C_{j,k}) - \mathbf{C}^{\text{real}}]$$

(22)

The calculation steps involved in the calibration procedure are summarized in Appendix B for reference.

To conduct the aforementioned calibration procedure using related statistical data, we generated an input database, which mainly included the potential annual physical amount associated with each facility location candidate, and the expected logistical distribution time between any two given location candidates in different layers of the proposed 3-layer PC supply chain framework. These input data correspond to the aforementioned real vectors $\mathbf{X}^{\text{real}}$ and $\mathbf{C}^{\text{real}}$ shown in Eq. (22), which will be utilized in *Step 1* of the proposed parameter calibration procedure (Appendix B).

The following summarizes the major procedures executed in the numerical study of model calibration. Using the statistics of the Chinese domestic PC market-sharing percentages collected in a series of reports by the Taiwan (2000a,b,c), a total of thirty major provinces and municipalities of China were clustered into seven regional groups. Herein, these targeted regions are regarded as the major sources for both the supply of PC assembling materials in layer S, and for the demand of PC products in layer D, as summarized in Table 1. Then five representative municipalities and seven others were selected as the facility location candidates for consideration of siting the corresponding manufacturing centers and regional logistical distribution centers in layers M and D, respectively. It is worth mentioning that according to the previous literature, these location candidates are reported to have relatively higher potential for conducting the corresponding activities of transnational PC manufacturing in China. Compared with other local regions, the location candidates may exhibit higher levels of the social and economic attributes, and more profitable environments for business operations in China.

Table 1
Candidates for facility locations in the proposed PC supply chain framework

Region	Sources of assembling materials layer S	Candidates of facility location for		Regional market sharing (%)	
		Layer M	Layer D	Supply	Demand
1. CE	Shanghai (municipality)	Shanghai (municipality)	Shanghai (municipality)	16	24
2. CN	Beijing (municipality)	Beijing (municipality)	Beijing (municipality)	29	28
3. CC	Hubei (province)		Wu–Han (municipality)	9	7
4. CS	Guangton (province)	Guangzhou and Fuzhou (municipality)	Guangzhou (municipality)	22	23
5. NE	Liaolin (province)	Shenyang (municipality)	Shenyang (municipality)	9	6
6. NW	Shanxi (province)		Xian (municipality)	7	3
7. SW	Sichuan (province)		Chengdu (municipality)	8	9

CE: Chinese eastern region; CN: Chinese northern region; CC: Chinese central region; CS: Chinese southern region; NE: Northern-east region; NW: Northern-west region; SW: Southern-west region.

Table 2
Statistical physical quantities of PC manufactured products and demands in China

The statistical amount of PC manufactured products in 2000						
Shanghai (municipality)	Beijing (municipality)	Guangton (province)	Fujen (province)	Liaolin (province)	Total	
420,400	3,367,700	2,287,000	887,900	837,000	7,800,000	

The statistical physical amounts of PC product demands in China							
CE region	CN region	CC region	CS region	NE region	NW region	SW region	Total
1,872,000	2,184,000	546,000	1,794,000	468,000	234,000	702,000	7,800,000

Given the pre-specified 3-layer PC supply chain framework coupled with potential facility locations in China, the following several procedures were conducted in this parameter calibration scenario. First, the potential physical amounts associated with these targeted regions were generated using the related historical data. For this, we collected the related historical data reported in Chinese annual statistics report (Institute for Information Industry, Taiwan, 2000a,b,c), and aggregated these data in Table 2. Secondly, the physical distribution times in any given distribution channels of the proposed framework, mimicking the corresponding real spatial interaction functions, were estimated. Herein, the geographic distances among these facility location candidates together with the forecast in terms of the local accessibility within the service area associated with each facility location candidate are considered. Data regarding inter-facility geographic distances can be collected readily from related literature (Wu, 2000). The estimate of local accessibility is determined mainly according to the levels of corresponding local social and economic attributes associated with the targeted provinces and municipalities. Details of the calibration procedure coupled with related numerical results are stated elsewhere (Lee, 2002), and so are omitted in this paper.

4. Applications

This section describes a numerical study which demonstrates the feasibility of the proposed model in determining the appropriate locations for siting both regional PC product manufacturing and distribution centers in China. [5]

Following the aforementioned decision-making logic proposed to determine the locations of the corresponding facilities in layers M and D, the execution steps together with the corresponding numerical results are summarized as follows. Given the input database determined previously, the state variables of the 3-layer supply chain-based spatial interaction system were forecasted using

---

[5] Herein, the generation of corresponding input database coupled with preliminary analyses of PC demand and supply market conditions in China are conducted previously in our related literature to alleviate the corresponding effects of demand and supply data bias on model's performance (Lee, 2002). Results of our preliminary analyses imply that short-term changes of PC market conditions in China may not have a significant effect on the long-term decision making for logistical network planning, and such a hypothesis may hold true in the next couple of years.

Table 3
Forecasted logistical distribution amounts in the 3-layer PC supply chain in China

From	To					From	To
	Manufacturing centers						
						From	To
Supply of assembling materials	Shanghai (municipality)	Beijing (municipality)	Guangzhou (municipality)	Fuzhou (municipality)	Shenyang (municipality)	Product demand
Shanghai (province)	68,525	548,935	372,781	144,728	136,431	
	100,896	808,248	548,880	213,096	200,880	CE region
Beijing (province)	123,598	990,104	672,378	261,043	246,078	
	117,712	942,956	640,360	248,612	234,360	CN region
Hubei (province)	36,995	296,358	201,256	78,135	73,656	
	29,428	235,739	160,090	62,153	58,590	CC region
Guangton (province)	34,893	279,519	189,821	73,696	69,471	
	96,692	774,571	526,010	204,217	192,510	CS region
Liaolin (province)	91,227	730,791	496,279	192,674	181,629	
	25,224	202,062	137,220	53,274	52,220	NE region
Shanxi (province)	37,416	299,725	203,543	79,023	74,493	
	12,612	101,031	68,610	26,637	25,110	NW region
Sichuan (province)	27,746	222,268	150,942	58,601	55,242	
	37,836	303,093	205,830	79,911	75,330	SW region

the proposed method, as addressed in *Step 1* of the proposed decision-making logic. The forecasted values of state variables are summarized in Table 3. Then, according to *Step 2*, the monetary measure associated with each facility candidate, e.g., δ_j and δ_k associated with layers M and D, was calculated, and herein the corresponding numerical results are summarized in Table 4. Utilizing the proposed decision-making rules presented in *Step 3*, the facility locations associated with layers M and D were then determined, as presented in Table 5. For this, the thresholds λ_M and λ_D were predetermined according to our interview surveys with 15 managers sampled from five transnational PC manufacturers in Taiwan in Spring, 2002 (Lin, 2002). Further discussions associated with these numerical results are described below.

In addition to physical quantities of inter-layer logistical distribution, Table 3 also provides the information referring to the present supply-demand relationships in given distribution channels of

Table 4
Calculated monetary measures

Estimated monetary measures associated with the location candidates in layer $M(\delta_j)$

Shanghai	Beijing	Guangzhou	Fuzhou	Shenyang
442	68	87	197	214

Estimated monetary measures associated with the location candidates in layer $D(\delta_k)$

Shanghai (CE region)	Beijing (CN region)	Wu–Han (CC region)	Guangzhou (CS region)	Shenyang (NE region)	Xian (NW region)	Chengdu (SW region)
613	92	123	286	306	176	314

Table 5
Determination of final facility locations

Layer M			Layer D		
Location	Measure $\left(\frac{\delta_j}{\sum_{\forall j \in M} \delta_j} \gamma_j\right)$	Priority	Location	Measure $\left(\frac{\delta_k}{\sum_{\forall k \in D} \delta_k} \gamma_k\right)$	Priority
Shanghai (CE)	663	1	Shanghai (CE)	147	1
Beijing	66	5	Beijing (CN)	26	4
Guangzhou	91	4	Wu–Han (CC)	9	6
Fuzhou (CS)	206	2	Guangzhou(CS)	66	2
Shenyang	143	3	Shenyang (NE)	18	5
			Xian (NW)	5	7
			Chengdu (SW)	28	3

the domestic PC market of China. Compared to the other candidates for facility locations in layer M, Beijing appears to surpass the others in both the demand and the supply markets for PC products. Nevertheless, the phenomenon of supply exceeding demand, where the value in a shadowed cell is less than the corresponding value in the un-shadowed cell, is observed in most inter-layer cases associated with Beijing. The most significant example can be found in the lo-gistical distribution channels for the Liaolin–Beijing–NE region, where the corresponding ratio of the supplied amount to the demand amount increases up to 3.62. Note that Liaolin is the rep-resentative supplier of assembling materials in the NE region. Accordingly, such a phenomenon implies that relatively greater investment risks resulting from supply overflows may exist in the Beijing location. Similar inferences also apply to the other location candidates.

In addition to Tables 3 and 4 provides another interesting implication for determining facility locations. Herein, the numerical results presented in Table 4 refer to the unit benefits of PC products associated with given facility locations, and thus may also reflect the potential rate of return on investment at each location candidate. Compared to the results of Table 3, it appears that Shanghai could replace Beijing as the first priority for siting corresponding facilities since it has the highest monetary measure, even though Beijing has the greatest logistical quantities on both the demand and supply sides. Following Shanghai, both Shenyang and Chengdu also show potential for yielding higher rates of return on investment than Beijing, despite the fact that their logistical amounts are much less than the corresponding value of Beijing in either the supply or demand market.

As can be seen in the shadowed regions of Table 5, two corresponding facility locations are suggested in both layers M and D, with the decision-making rules. Herein, the municipality of Shanghai, located in the CE region, is suggested as the first priority for siting both the PC manufacturing center and the distribution center. As the second priority, the municipalities of Fuzhou and Guangzhou, in the CS region, are also suggested for siting the manufacturing center and the distribution center, respectively, given the investment resources available. Such a final result appears reasonable, despite the fact that the present annual supply of PC products in Shanghai may not be competitive with either Beijing or Guangzhou. According to the numerical results, Shanghai appears to dominate the other facility locations in two primary aspects. The first is its relatively higher rate of return on investment, as reflected by the corresponding monetary measures (i.e., δ_j and δ_k). And the second is the corresponding demand-over-supply operational

status, which may contribute to the urgent necessity of expanding local corresponding facilities to satisfy the deficiency of PC supply volumes from Shanghai. It should also be noted that other superior operational conditions, such as the high degree of social and economic attributes, and the accessibility to international harbors and airports, can make Shanghai readily extend its distribution channels for PC global logistics. Similar factors may also apply to Fuzhou and Guangzhou.

Despite the applicability of the proposed method that has been demonstrated above, there are still some practical difficulties and limitations of data acquisition in this study, as follows. First, directly collecting nation-wide real data or surveys in China to ideally fit to our needs for the input data is impossible in the current phase. Such an issue could remain in any other studies, which aim at analyzing an emerging economy in a developing country using nation-wide data. Second, the related statistics reported officially by the corresponding governmental agencies of China are quite limited for further use in the analysis. Third, in-depth investigations in qualitative influencing factors, e.g., restrictions and incentives of local governmental regulations and the corresponding effects on inter-province logistical distribution activities, appear inadequate in the current study owing to limitations of time, manpower, and data sources. Our tentative solution is to incorporate these potential factors into the parameter calibration procedures, reflecting their corresponding effects on the magnitude of corresponding spatial interaction frictions.

5. Conclusion

This paper has presented an integrated supply-chain based spatial interaction model to deal with the facility location problems of transnational PC manufacturing in China. By specifying a 3-layer PC supply chain framework, and corresponding state variables, a spatial interaction model is formulated, and then followed by decision-making rules proposed to determine the locations of the corresponding facilities for PC manufacturing and distribution.

Compared to previous literature on facility location problems, the proposed method has two distinctive features. First, by coordinating the inter-layer logistical flows of a specified 3-layer PC supply chain, the proposed method can readily solve the chain-based multi-facility location problems for the transnational PC manufacturing and physical distribution in China. Second, factors including network-wide logistical costs and benefits, as well as economies of facility are considered in formulating the supply-chain based spatial interaction model, thus making the problem formulation more realistic.

Results from applying this model to a real study case study indicate that Shanghai has the highest potential advantages for transnational PC manufacturing enterprises to locate both manufacturing and distribution centers. In addition, the municipalities of Fuzhou and Guangzhou have the second highest priority for locating the manufacturing and product distribution centers, respectively.

The manager of a transnational PC manufacturing enterprise can conveniently use the proposed model as a decision-making support tool to help strategically determine priorities for locating corresponding facilities, according to the operational goals and overseas investment resources. In our future research, extension of the proposed model to formulate the globalized supply-chain based facility network design problems will be a topic of interest. Moreover, in-depth identification of qualitative influencing factors, e.g., overseas investment risks, trans-

national channel climate, market environmental variability, culture diversity, and label availability, also warrants more research for the extension.

Acknowledgements

Appendix A. Definitions of model variables and parameters

Definitions of variables and parameters in the proposed supply-chain based spatial interaction model are as follows:

- α_j = a positive parameter representing the effect of the economies of facility scale in terms of manufacturing associated with the given chain member j in the layer of manufacturing.
- α_k = a positive parameter representing the effect of the economies of facility scale in terms of inventory associated with the given chain member k in the layer of demand. [6]
- b_j = a parameter involved in the corresponding benefit function u_j to make the assumed exponential form hold.
- b_k = a parameter involved in the corresponding benefit function μ_k to make the assumed exponential forms hold.
- β_i = a parameter indicating the resisting effect on the corresponding manufacturing and logistics activities associated with a given chain member i in layer S.
- β_j = a parameter indicating the resisting effect on the corresponding manufacturing and logistics activities associated with a given chain member j in layer M.
- β_k = a parameter indicating the resisting effect on the corresponding manufacturing and logistics activities associated with a given chain member k in layer D.
- $\beta_{i,j}$ = a parameter reflecting the resisting effect on logistical distribution activities between the given chain members i and j.
- $\beta_{j,k}$ = a parameter reflecting the resisting effect on logistical distribution activities between the given chain members j and k.
- $\mathbf{C}(C_{i,j}, C_{j,k})$ = a $(I \cdot J + J \cdot K) \times 1$ vector of the spatial friction function which is composed of the estimated spatial friction functions ($C_{i,j}$ and $C_{j,k}$).

---

[6] Herein, α_j and α_k reflect the corresponding effects of the economies of facility scale on state variables in layers M and D. In general, greater values of these two parameters imply greater effects resulting from the corresponding facilities on the state variables, i.e., the amounts of physical flows.

- $C_{i,j}$ = the spatial interaction friction function associated with $x_{i,j}$.
- $C_{j,k}$ = the spatial interaction friction function associated with $x_{j,k}$.
- $\mathbf{C}^{\text{real}}$ = the real vector associated with $\mathbf{C}(C_{i,j}, C_{j,k})$ involving unknown real parameters.
- $\mathbf{F}\lfloor x_i, x_j^{\alpha_j}, x_k^{\alpha_k}, C \rfloor_{(I \cdot J + J \cdot K) \times 1}$ = a state-estimation function vector which depends on the physical quantities of logistics distribution associated with the chain members i, j, and k in layers S, M, and D, respectively (i.e., x_i, $x_j^{\alpha_j}$, and $x_k^{\alpha_k}$), and the corresponding spatial interaction friction functions (C for short).
- $f_{x_{i,j}}$ = the spatial interaction function proposed for the estimation of $x_{i,j}$.
- $f_{x_{j,k}}$ = the spatial interaction function proposed for the estimation of $x_{j,k}$.
- I = the number of chain members in the layer of supply (S for short).
- J = the number of chain members in the layer of manufacturing (M for short).
- K = the number of chain members in the layer of demand (D for short).
- γ_j = a market-oriented index [7] associated with the given facility location candidate j of layer M.
- γ_k = a market-oriented index [8] associated with the given facility location candidate k of layer D.
- $\mathbf{X}_{(I \cdot J + J \cdot K) \times 1}$ = $a(I \cdot J + J \cdot K) \times 1$ state vector which contains all the state variables specified in the proposed spatial interaction framework.
- $\mathbf{X}(x_j^{\alpha_j}, x_k^{\alpha_k})$ = $a(J + K) \times 1$ state estimation vector which contains the estimates of the physical amounts $x_j^{\alpha_j}$ in layer M and $x_k^{\alpha_k}$ in layer D.
- $\mathbf{X}^{\text{real}}$ = the real vector associated with $\mathbf{X}(x_j^{\alpha_j}, x_k^{\alpha_k})$, involving unknown real parameters.
- u_j = the given PC manufacturer's benefits originating from the physical amount of assembling materials distributed from chain layers S to M.
- μ_k = the given PC manufacturer's benefits originating from the physical amount of the PC product distributed from chain layers M to D.
- $\tilde{\mu}_{i,j}$ = the disaggregated net benefit index which accompanies the physical amount distributed between the given chain members i and j.
- $\tilde{\mu}_{j,k}$ = the disaggregated net benefit index which accompanies the physical amount distributed between the given chain members j and k.
- z = the objective function value.
- $\epsilon(\theta)$ = the calibration error vector calculated at any given iteration θ.
- δ_j = the monetary measure associated with a given facility candidate j of layer M.
- δ_k = the monetary measure associated with a given facility candidate k of layer D.
- λ_D = a pre-determined threshold decision of locating a given distribution center; λ_D is bounded by the values 0 and 1.
- λ_M = a pre-determined threshold for decision of locating a given manufacturing center; λ_M is bounded by the values 0 and 1.

---

[7] A value of γ_j greater than 1 may indicate that there is a deficiency of the supplied PC products from the given chain member j of layer M to satisfy the demands of layer D. Therefore, the higher the value of γ_j is, the more the corresponding monetary measure shown in Eq. (18) is amplified, which may prompt a final decision of siting a manufacturing center at the corresponding location.

[8] γ_k, referring to the proportion of the local demands to the total demands in the product demand market, may reflect the degree of relative significance of a given location candidate k, and thus is involved in the above decision-making rules for determining the corresponding distribution centers in layer D.

Appendix B. Model calibration

The major computational procedures conducted for model calibration are summarized below

Step 0: Initialization. Let the unknown real parameter vector ($\boldsymbol{\Phi}$) and the in-calibration parameter vector calibrated at iteration θ ($\boldsymbol{\Phi}(\theta)$) be given respectively by

$$\boldsymbol{\Phi} = [\alpha_j, \alpha_k, \beta_i, \beta_{i,j}, \beta_j, \beta_{j,k}, \beta_k, \quad i = 1, 2, \ldots, I; \; j = 1, 2, \ldots, J;$$
$$k = 1, 2, \ldots, K]^{\mathbf{T}}_{(I+2\cdot J+2\cdot K+I\cdot J+J\cdot K)\times 1} \tag{23}$$

$$\boldsymbol{\Phi}(\theta) = [\alpha_j^\theta, \alpha_k^\theta, \beta_i^\theta, \beta_{i,j}^\theta, \beta_j^\theta, \beta_{j,k}^\theta, \beta_k^\theta, \quad i = 1, 2, \ldots, I; \; j = 1, 2, \ldots, J;$$
$$k = 1, 2, \ldots, K]^{\mathbf{T}}_{(I+2\cdot J+2\cdot K+I\cdot J+J\cdot K)\times 1} \tag{24}$$

Furthermore,

$$\epsilon(\theta) = \boldsymbol{\Phi} - \boldsymbol{\Phi}(\theta) \tag{25}$$

In addition, let $\theta = 0$, and then give the initial values of the elements in $\boldsymbol{\Phi}(0)$; and specify the preset threshold vector ϵ used for terminating the calibration procedure.

Step 1: By using the first-degree Taylor series with respect to the real vectors $\mathbf{X}^{\text{real}}$ and $\mathbf{C}^{\text{real}}$, we have

$$\begin{bmatrix} \mathbf{X}^{\text{real}} - \mathbf{X}(\theta) \\ \mathbf{C}^{\text{real}} - \mathbf{C}(\theta) \end{bmatrix} = \begin{bmatrix} \partial \mathbf{X}(\theta)/\partial \boldsymbol{\Phi}(\theta) \\ \partial \mathbf{C}(\theta)/\partial \boldsymbol{\Phi}(\theta) \end{bmatrix} \epsilon(\theta) \tag{26}$$

Step 2: Use the Newton–Raphson method to search for $\epsilon(\theta)$, and then conduct the following termination rule:

If all the elements of $\epsilon(\theta)$ are less than the corresponding elements of $\epsilon(\theta - 1)$, then let

$$\boldsymbol{\Phi}^*(\theta + 1) = \boldsymbol{\Phi}(\theta) + \epsilon(\theta) \tag{27}$$

and let $\boldsymbol{\Phi}^*(\theta)$ be the targeted parameter vector calibrated for the use in the proposed model.

Otherwise, let

$$\boldsymbol{\Phi}(\theta + 1) = \boldsymbol{\Phi}(\theta) + \epsilon(\theta) \tag{28}$$

In addition, let $\theta = \theta + 1$, and then go back to *Step 1* to continue the calibration procedure at the next iteration.

References

Allen, K.M., 1991. The role of logistics in the overseas plant selection decision process of United States-based multinational corporations. Journal of Business Logistics 12 (2), 59–72.

Bean, J.C., Higle, J.L., Smith, R.L., 1992. Capacity expansion under stochastic demands. Operations Research 40, 210–216.

Beaumont, J.R., 1980. Spatial interaction models and the location–allocation problem. Journal of Regional Science 20, 37–50.

Bowersox, D.J., Closs, D.J., 1996a. Global logistics. In: Bowersonx, D.J., Closs, D.J. (Eds.), Logistical Management: The Integrated Supply Chain Process. McGraw-Hill, Singapore, pp. 129–135.

Bowersox, D.J., Closs, D.J., 1996b. Logistical operations integration. In: Bowersonx, D.J., Closs, D.J. (Eds.), Logistical Management: The Integrated Supply Chain Process. McGraw-Hill, Singapore, pp. 24–56.

Bramel, J., Simchi-Levi, D., 1997. Facility location models. In: Bramel, J., Simchi-Levi, D. (Eds.), The Logic of Logistics, Theory, Algorithms, and Applications for Logistics Management. Springer, Singapore, pp. 203–217.

Campbell, J.F., 1990. Locating transportation terminals to serve an expanding demand. Transportation Research 24B, 173–192.

Chen, L.-Y., 2001. The business opportunities and responses to the domestic markets of China, 2001. The Journal of Cross-Strait Economy and Trade, 112 (in Chinese).

Coelho, J.D., Wilson, A.G., 1976. The optimum location and size of shopping centers. Regional Studies 4, 413–421.

Cornuejols, G., Fisher, M.L., Nemhauser, G.L., 1977. Location of bank accounts to optimize float: an analytical study of exact and approximate algorithms. Management Science 23, 789–810.

Daganzo, C.F., 1987. The break-bulk role of terminals in many-to-many logistic networks. Operations Research 35, 543–555.

Daganzo, C.F., 1988. A comparison of in-vehicle and out-of-vehicle freight consolidation strategies. Transportation Research 22B, 173–180.

Daskin, M.S., 1995. Network and Discrete Location: Models Algorithms and Applications. John Wiley & Sons Ltd., New York.

Drezner, Z., Wesolowsky, G.O., 1980. Optimal location of a facility relative to area demands. Naval Research Logistics Quarterly 27, 199–206.

Drezner, Z., Wesolowsky, G.O., 1991. Facility location when demand is time dependent. Naval Research Logistics Quarterly 38, 763–777.

Erlenkotter, D., 1989. The general optimal market area model. Annuals of Operations Research 18, 45–70.

Erlenkotter, D., Leonardi, G., 1985. Facility location with spatially interactive travel behaviour. Sistemi Urbani 1, 29–41.

Evans, A.W., 1975. Least squares estimation of trip distribution models. Transportation Research 8, 105–122.

Friesz, T.L., Miller, T., Tobin, R.L., 1988. Algorithms for spatially competitive network facility-location. Environment and Planning B: Planning and Design 15, 191–203.

Ghosh, A., Craig, C.S., 1991. FRANSYS: a franchise distribution system location model. Journal of Retailing 67, 466–489.

Hakimi, S.L., 1964. Optimum location of switching centers and the absolute centers and medians of a graph. Operations Research 12, 450–459.

Hakimi, S.K., Kou, C.C., 1991. On a general network location–allocation problem. European Journal of Operational Research 55, 31–45.

Holmberg, K., 1996. Dual search procedures for the exact formulation of the simple plant location problem with spatial interaction. Location Science 4 (1), 83–100.

Hyman, G.M., 1983. The calibration of trip distribution models. Environment and Planning 8, 105–112.

Institute for Information Industry, Taiwan, 2000a. Analysis on the competitiveness and development of the PC regional markets in China. Analysis of Global Information Markets, Monthly Report, January 2000 (in Chinese).

Institute for Information Industry, Taiwan, 2000b. Business opportunities of the PC manufacturing industry under the present PC market competitive conditions in China. Analysis of Global Information Markets, Monthly Report, February 2000 (in Chinese).

Institute for Information Industry, Taiwan, 2000c. Developmental conditions of the PC displayer manufacturing in China. Analysis of Global Information Markets, Monthly Report, June 2000 (in Chinese).

Jacobsen, S.K., 1986. Plant location by entropy maximization. Research Report 10/86, IMSOR-DTH, Lyngby, Denmark.

Klincewicz, J.G., Luss, H., 1986. A lagrangian relaxation heuristic for capacitated facility location with single-source constraints. Journal of Operational Research Society 37, 495–500.

Lee, S.-S., 2002. Calibration of a novel spatial inaction model for the applications of PC manufacturing in China. Master Thesis, National Kaohsiung First University of Science and Technology, Taiwan.

Leonardi, G., 1978. Optimum facility location by accessibility maximizing. Environmental and Planning A 11, 1287–1305.

Leonardi, G., 1983. The use of random-utility theory in building location–allocation models. In: Thisse, J.F., Zoller, H.G. (Eds.), Location Analysis of Public Building Facilities. North-Holland Publishing Company, Amsterdam, pp. 357–383.

Lin, C.-W., 2002. The application of neuro-fuzzy approaches to global logistics of high-technology industries and case studies of the PC manufacturing enterprises of Taiwan. Master Thesis, National Kaohsiung First University of Science and Technology, Taiwan.

Miller, T., Tobin, R.L., Friesz, T.L., 1992. Network facility-location models in Staclkelberg–Nash–Cournot spatial competition. Regional Science 71, 277–291.

Mirchandani, P.B., Francis, R.L., 1990. Discrete Location Theory. John Wiley & Sons Ltd., New York.

Neebe, A.W., Rao, M.R., 1983. An algorithm for the fixed-charged assigning users to sources problem. Journal of Operational Research Society 34, 1107–1113.

Pirkul, H., Jayaraman, V., 1996. Production, transportation and distribution planning in a multi-commodity tri-echelon system. Transportation Science 30, 291–302.

Schemmer, R.W., 1982. Marketing Business Location Decisions. Prentice Hall, Englewood Cliffs, NJ.

Stetzer, F., 1983. Parameter estimation for the constrained gravity model: a comparison of six methods. Environment and Planning 8, 673–683.

Tong, H.-M., Walter, C.K., 1980. An empirical study of plant location decisions of foreign manufacturing investors in the United States. Columbia Journal of World Business 15 (1), 66–73.

Webster, S., Gupta, A., 1995. The general optimal market area model with uncertain and nonstationary demand. Location Science 3 (1), 25–38.

Wilson, A.G., 1969. A statistical theory of spatial distribution models. Transportation Research 1, 253–269.

Wu, L.-H., 2000. The Travel in China. Hwa-Tai Print Ltd., Taiwan (in Chinese).