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Cluster evolution of IC industry from Taiwan to China

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ABSTRACT

In this work, we for the first time study the inter-industrial clustering behaviors of integrated circuit (IC) industry from Taiwan to China via amount of foreign direct investment (FDI). According to the mutual dependence among IC design, manufacturing and packaging-and-testing industries, Lotka–Volterra model is solved to explore the cluster evolutions. Effects of inter-level collaborations along production value chain on FDI flows into China are considered. Evolution of FDI into China for IC design industry significantly inspires the subsequent FDI of IC manufacturing, packaging and testing industries. Since the production of IC manufacturing, packing and testing enterprises depends on the preceded products that design industry has devised, the middle-stream manufacturing and downstream packaging-and-testing firms tend to converge toward upstream design houses. Taiwan IC industry's FDI amount into China is estimated to be cumulatively increasing, which suggests the clustering tendency of Taiwan IC industry. Prediction of FDI with Lotka–Volterra model is superior to that of the conventional growth model (i.e., Bass model) because the industrial mutualism among various stages is included. The flows of FDI have not yet reached equilibrium points, so the FDI inflows into China will expand for IC design or packaging-and-testing industry, while decline for manufacturing industry.

1. Introduction

Industrial clustering has recently received increasing attention from academic and practical fields. Prior literature in business fields mostly applies qualitative research to map industrial clusters [1–3], to identify the spatial concentrations of related firms as industrial clusters [4], or to compare the difference in knowledge sharing and innovation achievements between industrial clusters and other areas without the phenomenon [5,6]. Many studies also emphasize that Taiwan integrated circuit (IC) enterprises cluster together in Hsinchu Science Industrial Park (HSIP), and the intimacy among employees, suppliers and customers in HSIP accordingly accelerates information interchanges and technique upgrades within the clustered enterprises [5,7]. Thus, Taiwan's IC industry has long maintained the worldwide leading position through such clustering economic systems. The global market shares of Taiwan's foundry IC manufacturing, packaging and testing industries have been all the largest and the global market share of Taiwan's IC design industry has long ranked number two since 2000. In addition to the visible clustering of firms in specific geological location (e.g. HSIP), alternative literature further addresses the industrial cluster formation from Taiwan to China [8,9]. The previously-experienced foreign direct investment (FDI) firms in Taiwan IC industry have attracted other IC firms to successively undertake FDI as well as construct business bases in China [9]. FDI of Taiwanese firms in China is defined as the capital flow from a foreign country (here, Taiwan) to a host country (China) to establish production facilities and conduct business activities. We in that study utilize conventional diffusion theory to estimate the industrial clustering evolutions via Bass model [10,11]. However, Bass model assumes the market monopolistic [12–15], so reciprocal cooperation or competition among different production layers within the same class of industry has been ignored in such studies. There remains, for now, a scarcity of literature

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that considers the effect of reciprocal interactions along the industrial value chain on clustering evolutions. It is worthwhile to adopt a model that explicitly incorporates the mutual dependence along the production value chain.

In this work, we present vertically collaborative mutualism of Taiwan's IC industry within its industrial clustering evolutions to China since the worldwide leading position of Taiwan's IC industry is characterized by its vertical disintegration structure [16,17]. According to industrial organization theory, vertical disintegration means subdividing an industry into several levels along the value chain, and letting the firms at each level focus on their own specialization [18]. The independent Taiwanese IC firms separately specialize in upstream IC design, midstream IC manufacturing, or downstream IC packaging-and-testing sectors, so they can smoothly keep pace with and be well-informed of the upstream suppliers and downstream clients or markets. The reciprocal dependence and mutual supports are fairly profound in information sharing, manufacturing, logistics, and innovation of Taiwan IC industry, distinctly different from the integrated device manufacturers (IDM) in U.S., Japanese, and Korean IC fields. We are the first attempt to introduce the Lotka–Volterra model in addressing the inter-level cooperative effects on clustering formation. Lotka–Volterra model has been developed to model the interaction between the two competing species based on the logistic curve and extended on the analysis of technology diffusion in competitive or collaborative markets covered in relevant literature [19–22]. Hence, the adopted Lotka–Volterra model is capable of explicitly capturing the inter-level competition or collaboration under vertical disintegration structure. Our investigation may benefit enterprises' strategic planning and operational management, in which the competitions or collaborations are extremely important dimensions of industrial frameworks.

This study highlights the dynamical competition derived from industrial clustering evolutions. The inter-sector competitive effects on FDI flows are taken into account in our study; it initially groups in pairs the foreign direct investment (FDI) values of the three industries: IC design, IC manufacturing, and IC packaging-and-testing industries. While the three FDI values are in turn grouped into three comparative pairs, Lotka–Volterra model is introduced to investigate the reciprocal influence among these three industries. If one pair of FDI values is found to have an increasing lead–lag relationship, then inter-industry clustering may be explicitly proved. This examination is further advanced to forecast the trend of Taiwan's IC industrial clustering to China, and the accuracy comparison is conducted between the Lotka–Volterra model and the Bass model. This research verifies whether the Lotka–Volterra model, which specifies the inter-industrial reciprocal competitions, performs better than the Bass model. Finally, the characteristics of the dynamic collaborative relations within Taiwan's IC industry FDI into China are examined, including the existence of an equilibrium point and its stability with the estimated functions.

The organization of this paper is as follows. In the next section, background is illustrated. In the third section, methodology and sample used are rendered. In the fourth section, the results are provided, and a dynamic competition analysis, including the equilibrium analysis, is performed. Finally, we draw the conclusion.

2. Background

Taiwan's IC industry is concentrated in the vicinity of Hsinchu Science Industrial Park where numerous producers are interconnected and interdependent in production, marketing, operation, logistics and technology diffusion. Due to clustering theory, agglomeration of Taiwan's IC industry creates a pooled platform for workers with specialized skills to exchange experiences and share information. The modulation, coordination and integration of these neighboring IC firms allow Taiwan's IC industry to efficiently handle abrupt crises, continuously upgrade technological levels and develop new products.

Specifically, the framework of Taiwan's IC industry belongs to vertical disintegration structure. The independent IC firms separately specialize in upstream IC design, midstream IC manufacturing, or downstream IC packaging-and-testing sectors. Under the premise that Taiwan's IC design firms ought to respond to their market demand as soon as possible to satisfy their final market (consumer electronics and PC markets) with their designed products, these IC design firms need to work closely with IC manufacturing foundries to flexibly manufacture versatile products to achieve customers' acceptance. Thus, the reciprocal dependence is manifest among upstream IC design and midstream IC manufacturing enterprises. In addition, Taiwan IC packagers and testers continuously provide IC manufacturing firms with reliable turnkey services, strengthening their tight cooperation with each other as well. As we can see from the above explanations, each sector along Taiwanese IC industry production is not only reciprocally dependent, but also mutually supportive to each other. These IC firms' collaborative team work has enabled Taiwan to hold the leading position in the worldwide semiconductor industry.

In recent years, Taiwan's IC firms have gradually encountered the problems of high labor wages, so some of them have aggressively shifted their manufacture bases abroad. According to a survey conducted by the Taiwan Electricity and Electronic Manufacturer Association (TEEMA), China has offered cheaper lands, lower labor costs, preferential tax treatment, strong political enforcement, policy stability, bureaucratic efficiency and administrative support for foreign enterprises, especially after the economic reforms in 1990s [23]. Driven by Taiwan's labor cost pressure and China's opportunities, most of Taiwan's IC firms have implemented FDIs and relocated their production into China since 1990s. Owing to the inter-level reciprocal dependence under the vertical industrial disintegration structure, Taiwanese IC enterprises' strategy to invest in China has become efficient and effective once their upstream suppliers or downstream customers lie within the host country (China). As a result, industrial clustering has become well-established. Ultimately, IC related industries through all production processes, from upstream IC design to downstream IC packaging-and-testing, end up instituting divisions in China. Shanghai, Shenzhen and their neighboring regions (Suzhou, Kunshan and Wujiang) have become the primary destinations for cross-Strait investment from Taiwan to China. Taiwanese IC firms as a whole have contributed to the rapid growth of Chinese IC industry and a new IC industrial cluster has thus evolved in China.

3. Methodology and sample data

3.1. Lotka–Volterra model

The Lotka–Volterra model uses the logistic equation as basis, plus a term accounting for the interaction with the other species. The interaction between two species can be expressed in two differential equations as follows [21,22]:

$$\frac{dX}{dt} = (a_1 - b_1X - c_1Y)X = a_1X - b_1X^2 - c_1XY, \tag{1}$$

and

$$\frac{dY}{dt} = (a_2 - b_2Y - c_2X)Y = a_2Y - b_2Y^2 - c_2YX, \tag{2}$$

where X and Y represent the populations of two competing species at time t. The above system of equations contains all fundamental parameters that affect the growth rate of both species. In Eqs. (1) and (2), X^2 and Y^2 terms represent the same species interacting internally with itself, while the terms XY and YX show different species interacting with the other. a_i is the logistic parameter of geometric growth for the species i when it is living alone, b_i is the limitation parameter of the niche capacity for the species i, and c_i generally called the coupling coefficient, is the interaction parameter with the other species. The multi-mode form can be illustrated by the coefficient c_i for the case of two species. The types of competitive roles according to the signs of c_i [24], so the multi-mode form could be revealed for the case of two species in Table 1.

To use discrete time data, it is necessary to covert the continuous Lotka–Volterra model into a discrete time version. Eqs. (1) and (2) could be transformed into difference equations [25]:

$$X(t+1) = \frac{\alpha_1X(t)}{1 + \beta_1X(t) + \gamma_1Y(t)}, \tag{3}$$

and

$$Y(t+1) = \frac{\alpha_2Y(t)}{1 + \beta_2Y(t) + \gamma_2X(t)}. \tag{4}$$

In Eqs. (3) and (4), α_i and β_i are the logistic parameters for the single species i when it is living alone. γ_i expresses the magnitude of the effects that one species has on the growth rate of the other. The relations between coefficients of continuous Lotka–Volterra model and those of the transformed difference Eqs. (3) and (4) are:

$$a_i = ln\alpha_i. \tag{5}$$

$$b_i = \frac{\beta_i a_i}{\alpha_i - 1} = \frac{\beta_i ln\alpha_i}{\alpha_i - 1}. \tag{6}$$

$$c_i = \gamma_i\frac{b_i}{\beta_i} = \frac{\gamma_i}{\beta_i}\frac{\beta_i ln\alpha_i}{\alpha_i - 1} = \frac{\gamma_i ln\alpha_i}{\alpha_i - 1}. \tag{7}$$

The sign of γ_i must be the same as the sign of c_i since $\frac{ln\alpha_i}{\alpha_i - 1}$ is always positive if $\alpha_i>0$ and $\alpha_i \neq 1$ in Eq. (7). Thus, the type of competitive roles in Table 1 can be determined according to the sign of γ_i.

3.2. Assumptions

We assume that the clustering evolutions of Taiwan IC industries in China correspond to the original condition of Lotka–Volterra model. Since prior literature has never ascertained whether mutual dependence exists among each sector along IC industry, this study seeks to verify the reciprocal influence of industrial clustering evolutions two by two among the three

Table 1
Multi-mode competitive relationship according to the signs of interaction parameters.

c_1	c_2	Type	Explanation
+	+	Pure competition	Both species suffer from each other's existence.
+	−	Predator–prey	One of them serves as direct food to the other.
−	−	Mutualism	It is the case of symbiosis or a win–win situation.
+	0	Amensalism	One suffers from the existence of the other, who is impervious to what is happening.
−	0	Commensalism	One benefits from the existence of the other, who nevertheless remains unaffected.
0	0	Neutralism	There is no interaction.

industries (IC design, IC manufacturing, along with IC packaging-and-testing industries). This work groups FDI values of the three industries in pairs. While the three FDI values are in turn grouped into three comparative pairs, three pairs of system equations (Eqs. (3) and (4)) are examined separately to determine the three mutual inter-industry impacts in Taiwan's IC field. Thus, in Eqs. (3) and (4), X and Y stand for the two of the three cumulative FDI values along Taiwan's IC industrial value chain. The cumulative FDI value is defined as the total FDI amount remitting to China minus the total amount returning to Taiwan. α_i and β_i are the logistic parameters for one single industry. γ_i expresses the magnitude of the effects that one industry's FDI has on the FDI growth rate of the other.

3.3. Comparison with Bass model

To further demonstrate the performance of Lotka–Volterra model, we also solve the Bass model [10]. Under several assumptions [10,11], the dynamics of FDI growth for each industry in Bass model is of the form:

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = (p + qN(t))(M - N(t)), \tag{8}$$

where $N(t)$ is the cumulative FDI amount at time t, and M is the potential size of FDI into China. The parameter p is called the coefficient of innovation, and q the coefficient of imitation. After FDI amount is estimated by Bass or Lotka–Volterra model, the prediction ability of Bass model is compared with that of Lotka–Volterra model based on mean absolute prediction error (MAPE). This MAPE is calculated by $\mathrm{MAPE} = \frac{1}{n}\sum_{t=1}^{n}\frac{|Y_t - \hat{Y}_t|}{Y_t}$, where Y_t and $\hat{Y}_t$ represent the realistic and predicted FDI at time t and n is the number of observations. The calculated errors could manifest which model is more efficient.

3.4. Equilibrium analysis

The analysis of competitive relationship by Lotka–Volterra model can provide information as regards what the equilibrium state is and how the trajectory changes over time. Additionally, the stability of equilibrium can be clearly identified. In equilibrium, Eqs. (1) and (2) must be zero because there are no simultaneous changes over time for each industry:

$$\frac{\mathrm{d}X}{\mathrm{d}t} = 0 \quad \text{and} \quad \frac{\mathrm{d}Y}{\mathrm{d}t} = 0. \tag{9}$$

By applying condition (9) to Eqs. (1) and (2), the following system of equations is obtained:

$$\begin{aligned} &a_1X - b_1X^2 - c_1XY = X(a_1 - b_1X - c_1Y) = 0, \text{ and} \\ &a_2Y - b_2Y^2 - c_2XY = Y(a_2 - b_2Y - c_2X) = 0 \end{aligned} \tag{10}$$

Solving the system of Eq. (10) will result in

$$X = \frac{a_1 - c_1Y}{b_1}, \quad \textit{and} \quad Y = \frac{a_2 - c_2X}{b_2}. \tag{11}$$

The two lines $\mathrm{d}X/\mathrm{d}t = 0$ and $\mathrm{d}Y/\mathrm{d}t = 0$ are crossing each other, which implies that there exists an equilibrium point. In Eqs. (10) and (11), if $X < \frac{a_1 - c_1Y}{b_1}$, then $\mathrm{d}X/\mathrm{d}t > 0$. Conversely, if $X > \frac{a_1 - c_1Y}{b_1}$, then $\mathrm{d}X/\mathrm{d}t < 0$. Similarly, $\mathrm{d}Y/\mathrm{d}t > 0$ if $Y < \frac{a_2 - c_2X}{b_2}$, and $\mathrm{d}Y/\mathrm{d}t < 0$ if $Y > \frac{a_2 - c_2X}{b_2}$.

The stability of equilibrium point depends on the values of the coefficients in the Lotka–Volterra model [26], so its stability conditions are initially conducted. After the stability of equilibrium points are proved, we compare the realistic FDI amount with the equilibrium point value to highlight the IC industrial dynamics in the future. If the two straight lines expressed in Eq. (11) intersect each other in the first quadrant, the pair of the industrial FDI flows into China is expected to coexist without any dynamic changes. If the two straight lines expressed in Eq. (11) intersect each other in the second or fourth quadrant, this equilibrium point informs us that only one of these two IC industrial FDIs will still sustain in China. In the future, the other IC industry is expected to withdraw their FDIs in China.

3.5. Data and sample

The sample includes sixty-four IC public firms of Taiwan: forty-six IC design firms, five IC manufacturing firms, thirteen IC packaging-and-testing firms. The investigated time period is from 2000 to 2007 and the sample data is measured in New Taiwan (NT) dollars (thousands). The collected FDI amount is defined as the net FDI amount to China, namely, the FDI amount remitting to China minus the amount returning to Taiwan. The data of collected and permitted amount of FDI to China are collected from Taiwan Economic Journal (TEJ) database. Taiwan Economic Journal (TEJ) database collected the FDI data from each firm's FDI application form to Ministry of Economics Affairs, Taiwan. Because FDI flows inspire the movement of factories, equipments and technological

Table 2
Coefficient estimation of discrete time Lotka–Volterra model.

Pair one	Design		Manufacturing	
	Coefficient	*t*-statistic	Coefficient	*t*-statistic
α	1.1688	23.2737***	1.804507	6.5085***
β	2.66×10^{-8}	1.3786	9.03×10^{-8}	4.1696***
γ	-1.19×10^{-9}	−0.2297	-8.45×10^{-8}	−1.8469*
R^2	0.9953		0.9932	
Pair two	Design		Packaging-and-testing	
	Coefficient	*t*-statistic	Coefficient	*t*-statistic
α	1.1689	12.5884***	0.78167	10.46624***
β	3.54×10^{-8}	0.8149	5.09×10^{-8}	8.6129***
γ	-4.88×10^{-9}	−0.4488	-1.82×10^{-7}	−6.9244***
R^2	0.9928		0.9814	
Pair three	Manufacturing		Packaging-and-testing	
	Coefficient	*t*-statistic	Coefficient	*t*-statistic
α	2.1916	6.5817***	1.2198	15.4643***
β	1.09×10^{-7}	3.2138***	1.73×10^{-78}	3.3260***
γ	-2.33×10^{-8}	−1.4962	-6.67×10^{-79}	−0.8909
R^2	0.9814		0.9920	

The coefficients of discrete time Lotka–Volterra model can be transformed into those of continuous Lotka–Volterra models, namely, $a_i = \ln\alpha_i$, $b_i = \frac{\beta_i \ln\alpha_i}{\alpha_i - 1}$, and $c_i = \frac{\gamma_i \ln\alpha_i}{\alpha_i - 1}$.
Notes: $^{***}p \leq 0.01$; $^{*}p \leq 0.1$.

skills to settle down abroad, FDI is an objectively quantified indicator of industrial formation. Thus, we choose FDI flows as the industrial evolution indicators.

4. Results and discussion

4.1. Competitive relationship analysis

The quarterly FDI amount to China of the three IC industries from the first quarter of 2000 to the fourth quarter of 2007 was used to estimate the demand function and the estimated coefficients and related statistics are shown in Table 2. For the IC design and manufacturing industries (pair one), the interaction parameter is significantly negative in the IC manufacturing industry while insignificant for the IC design industry. These results indicate that the evolution of FDI toward China for IC design industry

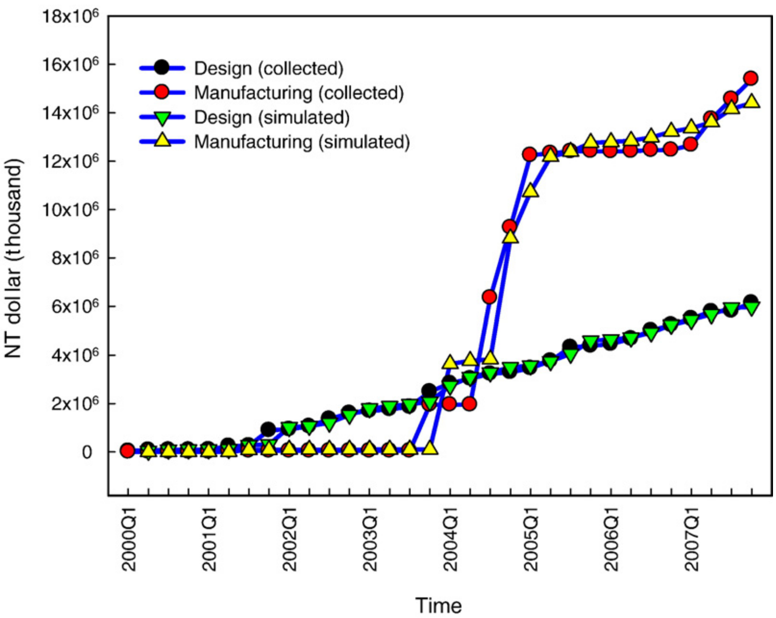

Fig. 1. Simulated and collected FDI amount for IC manufacturing and IC design industries based on Lotka–Volterra competition equations.

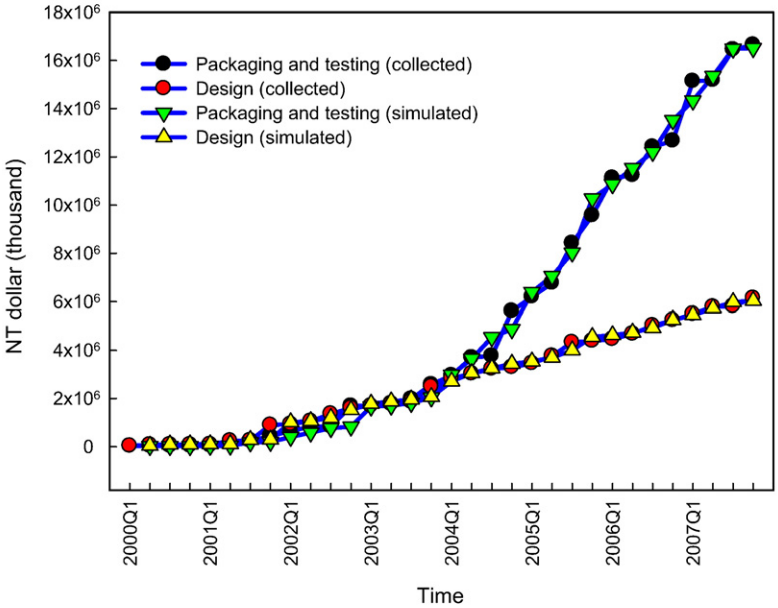

Fig. 2. Simulated and collected FDI amount for IC packaging-and-testing and IC design industries based on Lotka–Volterra competition equations.

significantly inspires the subsequent FDI of IC manufacturing industry, though FDIs of IC design industry are unaffected by IC manufacturing industry. In other words, commensalism relation exists between IC design and manufacturing industries.

For IC design and packaging-and-testing industries (pair two), the interaction parameter is significantly negative in IC packaging-and-testing industry while insignificant for IC design industry. These results indicate that the evolution of FDI toward China for IC design industry significantly inspires the subsequent FDI of IC packaging-and-testing industries, though FDIs of IC design industry are unaffected by IC packaging-and-testing industry. In other words, commensalism relation exists between IC design industry and packagers-and-testers.

The result contains an intuitive interpretation: IC deign industry features differently in its designed products (such as CPU, chipset, mobile phone, power supply management and cartography), so various IC design products require different manufacturing process or techniques of midstream IC manufacturing and downstream IC packaging-and-testing industries. In

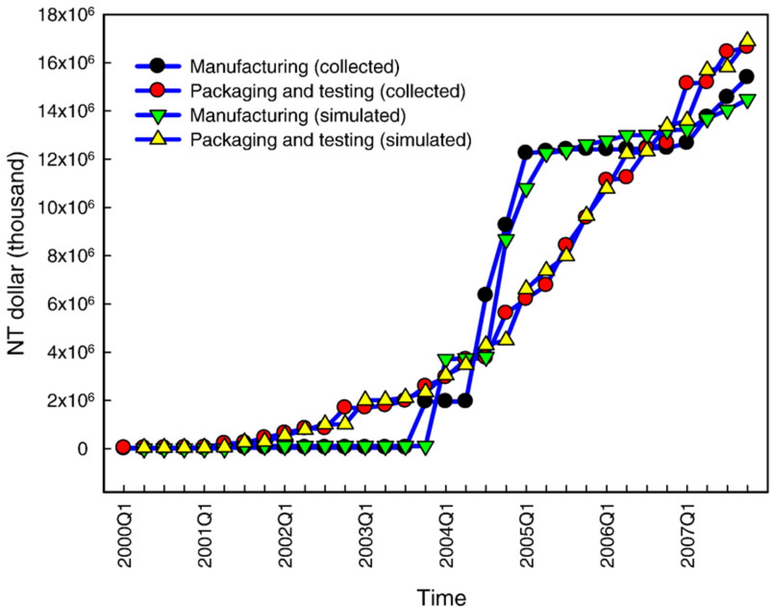

Fig. 3. Simulated and collected FDI amount for IC packaging-and-testing and IC manufacturing industries based on Lotka–Volterra competition equations.

other words, the producing skills of IC manufacturing or packaging-and-testing industry vary with the specifications of each unique IC design product.

Under this circumstance, it is only when IC design industry gets involved in FDI into China will the manufacturing, packaging and testing industries subsequently decide whether they ought to engage in the same FDI project. That is, since IC manufacturing, packaging and testing industries depend on design industry for advanced business benefits, if design houses move to China, manufacturing, packaging and testing firms would also cluster together into China. On the contrary, if the IC manufacturing, packaging and testing houses are to be relocated in China, the design houses will hardly be affected because manufacturing, packaging or testing skills fail to influence design products. Few IC design houses would actively respond to FDI decisions of manufacturing, packaging and testing industries to undertake their FDIs.

For the IC manufacturing and packaging-and-testing industries (pair three), the interaction parameters are all negative yet insignificant for both industries. FDI of the IC manufacturing industry does not obviously affect that of the packaging-and-testing industry, and vice versa. This can be possibly interpreted by the governmental policy change on manufacturing firms. IC foundry manufacturing industry was strictly prohibited from FDI in China by Taiwanese government before 2003, while the restriction was relaxed after 2003. Huge amount of capital flows remitted to China only after the government approved the applications of FDI

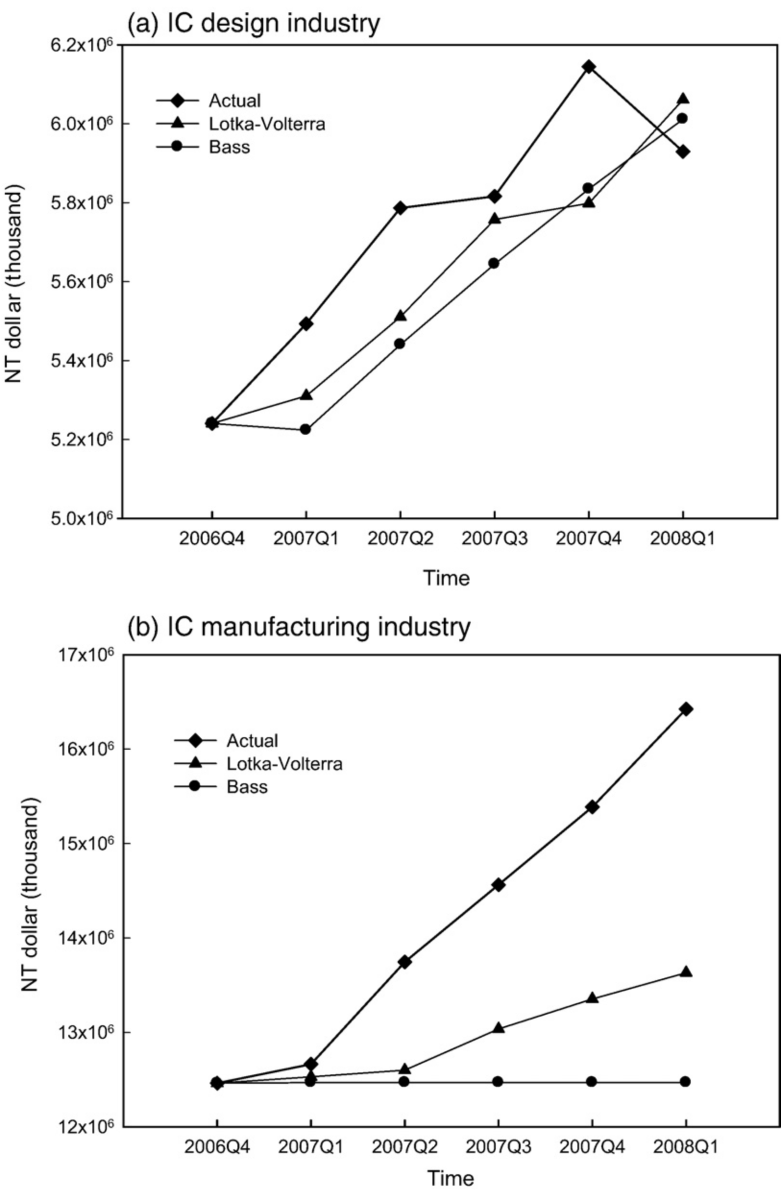

Fig. 4. Comparison among the realistic FDIs, Bass simulated results and Lotka–Volterra simulated results based on the pairs of IC design and IC manufacturing industries.

from IC manufacturing firms. Thus, the policy change deters the relations to become unapparent among FDI series for IC manufacturing, packaging and testing industries.

The collected FDI amount and simulated FDI amount by Lotka–Volterra model for the three pairs of IC industries are depicted in Figs. 1–3. As can be seen in the graphs of Figs. 1–3 that the estimated FDI function shows almost the same trend as the collected data does, which implies that the Lotka–Volterra model well explains the evolution process of Taiwan IC industry into China. In regards to the time-series pattern of FDI, Taiwan IC industry's FDI amount into China is assessed to cumulatively increase and interactively related among each stage along IC value chain. Once more and more IC firms build up production bases in one specific location, the other IC related enterprises are likely to congregate in such neighboring areas. Hence, they can easily access the available materials, basic equipment and suppliers' resources over this region. This finding once again supports the industrial clustering tendency for IC business. Besides, the finding controverts the claim that Taiwan government closes its country gate to international intercourse or prohibits its enterprises from foreign investment.

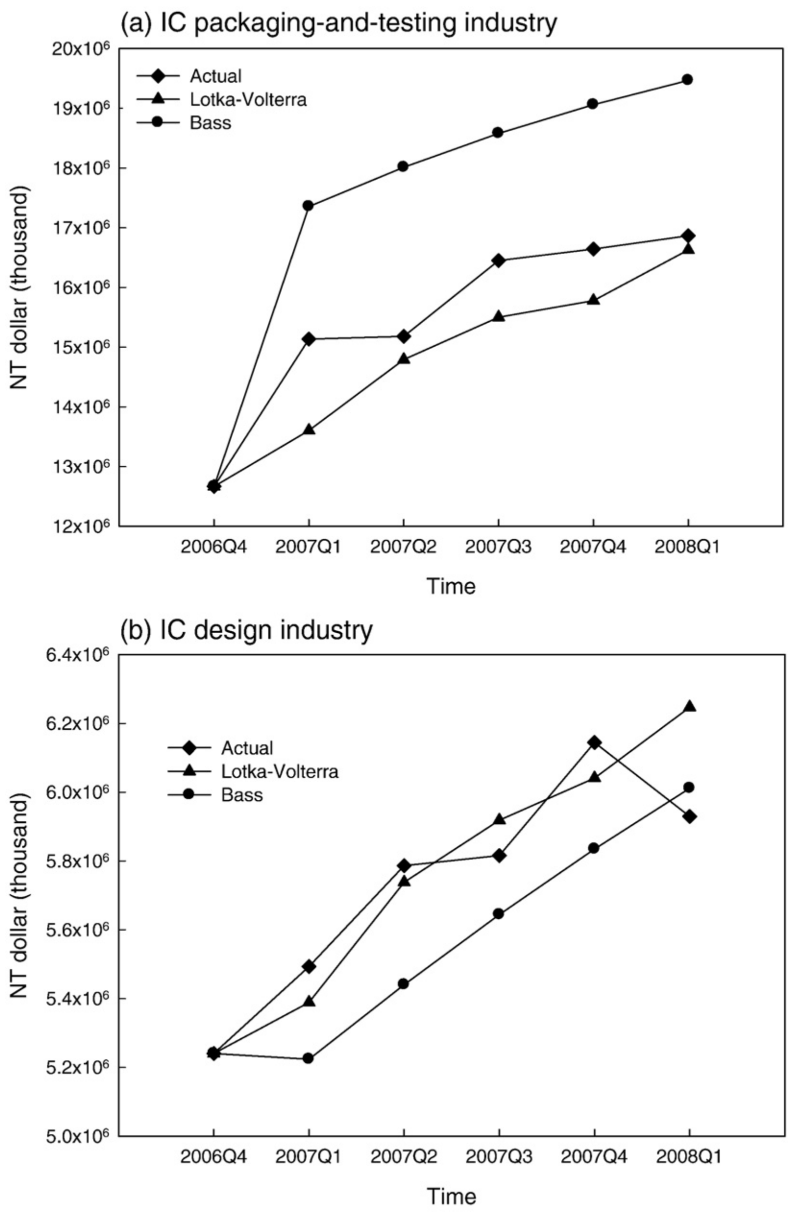

Fig. 5. Comparison among the realistic FDIs, Bass simulated results and Lotka–Volterra simulated results based on the pairs of IC design and IC packaging-and-testing industries.

4.2. Performance comparison

The prediction ability is compared between the Bass model and the Lotka–Volterra model. To do so, the parameters of both models are estimated with the quarterly FDI amount to China up to the fourth quarter of 2006, and then the forecasts of quarterly FDI amount from the first quarter of 2007 to the first quarter of 2008 are compared with the actual realistic quarterly FDI amount. Comparison between the simulation and realistic FDIs is shown in Figs. 4–6. The computed FDIs versus the time for the calculation with Bass and Lotka–Volterra model are plotted. It can be obviously observed from these figures that the results computed by Bass model shift away from the realistic data. Simulated FDIs by Lotka–Volterra model are closer to the actual FDIs than the simulated FDIs by Bass model.

Moreover, the forecasting errors of each model are measured by MAPE (mean absolute percentage prediction error) and presented in Table 3. The results show that MAPE of the Bass model is two times higher than that of Lotka–Volterra model in IC packaging-and-testing industrial FDI amount to China. Besides, MAPE is also higher in IC design or manufacturing industry for Bass model than Lotka–Volterra model. The estimation of FDI of Lotka–Volterra model performs superior to that of the conventional Bass model. The evidences suggest that the prediction ability is dramatically improved as the industrial mutualism relation among

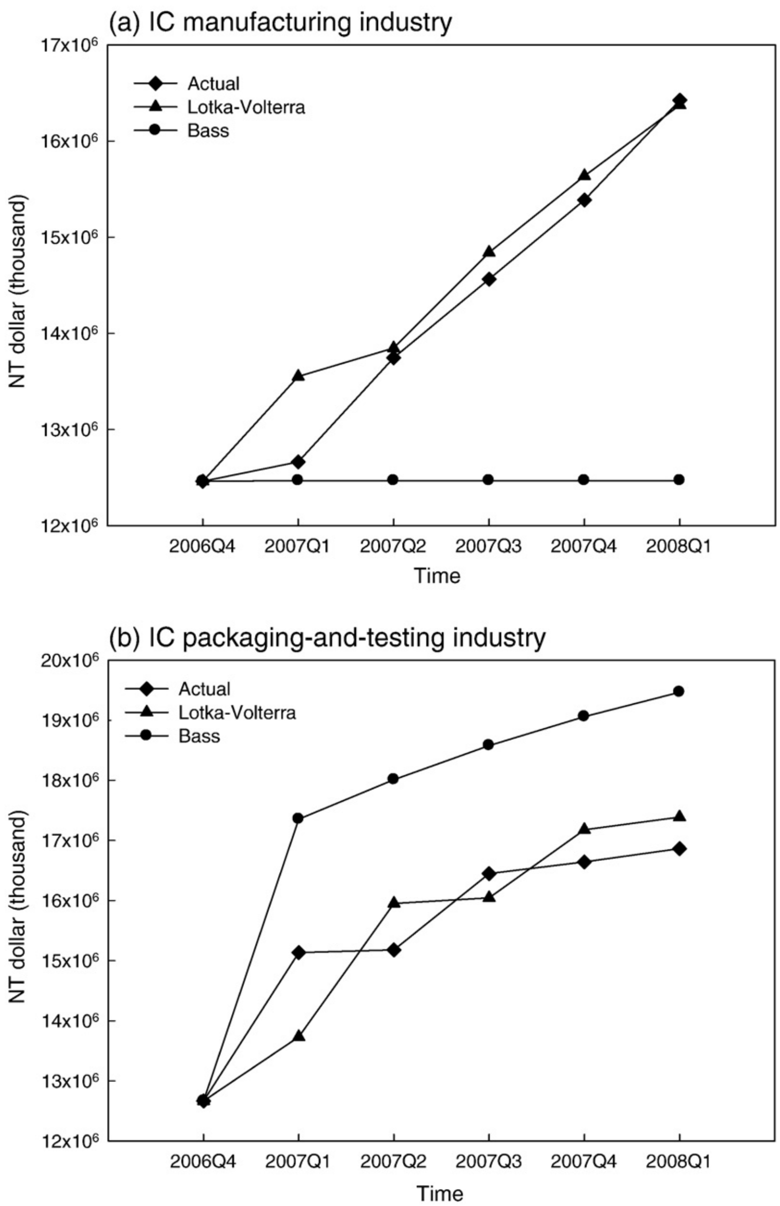

Fig. 6. Comparison among the realistic FDIs, Bass simulated results and Lotka–Volterra simulated results based on the pairs of IC manufacturing and IC packaging-and-testing industries.

Table 3
Mean absolute percentage prediction errors (MAPEs) of Bass model and Lotka–Volterra models from the first quarter of 2007 to the first quarter of 2008.

	Bass	Lotka–Volterra		
		Design and manufacturing	Packing-and-testing and manufacturing	Design and packing-and-testing
Design	0.0405	0.0339		0.0231
Manufacturing	0.1365	0.1002	0.0232	
Packaging and testing	0.1524		0.0463	0.0501

This MAPE is calculated by MAPE $= \frac{1}{n}\sum_{t=1}^{n}\frac{|Y_t - \hat{Y}_t|}{Y_t}$, where Y_t and $\hat{Y}_t$ represent the realistic and predicted FDI at time t.

each IC production stage is taken into account. It is strongly recommended to use the competitive diffusion model like Lotka–Volterra model when analyzing industrial clustering evolutions under vertical disintegration structure.

4.3. Equilibrium points

By substituting the values of α_i, β_i, and γ_i in Table 2 into Eqs. (5)–(7), a_i, b_i, and c_i will be obtained. Two linear functions for equilibrium analysis can be further obtained by inserting the values a_i, b_i, and c_i into Eq. (11). The equilibrium point between the IC design and packaging-and-testing industries is illustrated in Fig. 7. The two straight lines developed in Eq. (11) intersect each other in the first quadrant, so these two series of FDI amount have an equilibrium point. Through the coefficients a_i, b_i, and c_i the equilibrium point is satisfied with the stable conditions.

The area with horizontal hatchings represents the region where the FDI amount of IC packaging-and-testing industry will increase ($dX/dt<0$), while the area marked with vertical hatchings represents the region where the FDI amount of IC design industry will increase ($dY/dt<0$). Hence, in the area with checkers, both industries' FDI amounts from Taiwan to China will increase. As for the first quarter of 2008, the FDI amounts were 16,865 millions and 5,929 millions, respectively for the IC packaging-and-testing industry and the IC design industry. The numbers correspond to a point in the area with checkers, and indicate that the two IC industries have not reached their equilibrium point (25,167 and 8,238 millions, respectively) and that both industries' FDIs from Taiwan to China are still expanding.

Considering the relationship between IC design and manufacturing industries, their equilibrium point is shown in Fig. 8. The two straight lines developed in Eq. (11) intersect each other in the first quadrant, so these two series of FDI amount have an equilibrium point here. Their equilibrium point is also proved to be stable since their coefficients satisfy the balance conditions. The area with horizontal hatchings represents the region where the FDI amount of IC design industry will increase ($dX/dt>0$), while the area marked with vertical hatchings represents the region where the FDI amount of IC manufacturing industry will decrease ($dY/dt<0$). Hence, in the area with checkers, the FDI amount of IC packaging-and-testing industries from Taiwan to China will increase, while the FDI amount of IC manufacturing industry will decrease. As for the first quarter of 2008, the FDI amounts were 16,425 millions and 5,929 millions, respectively for IC manufacturing industry and IC design industry. That numbers correspond to a point in the area with checkers, and indicate that the two IC industries have not yet reached their equilibrium point (15,496 and

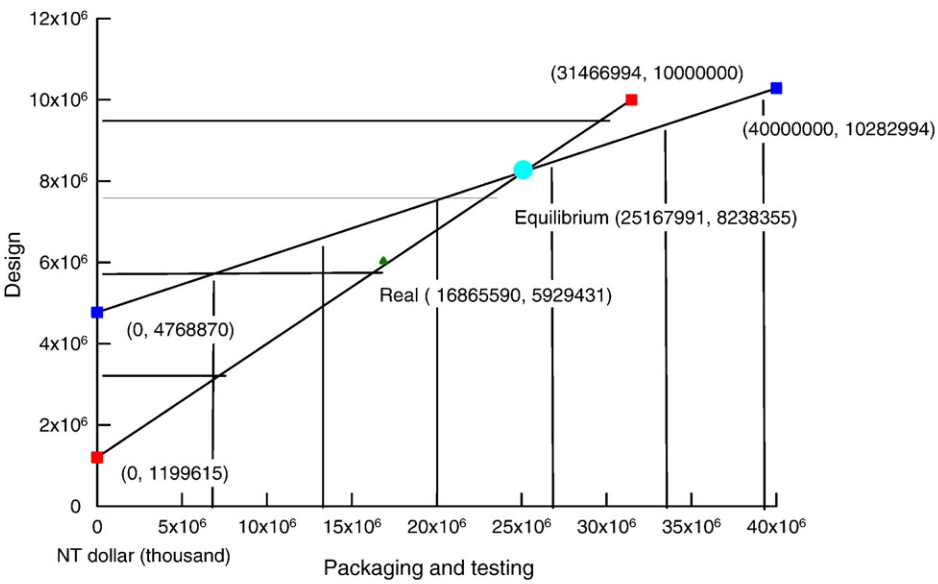

Fig. 7. Equilibrium point between IC design and IC packaging-and-testing industries.

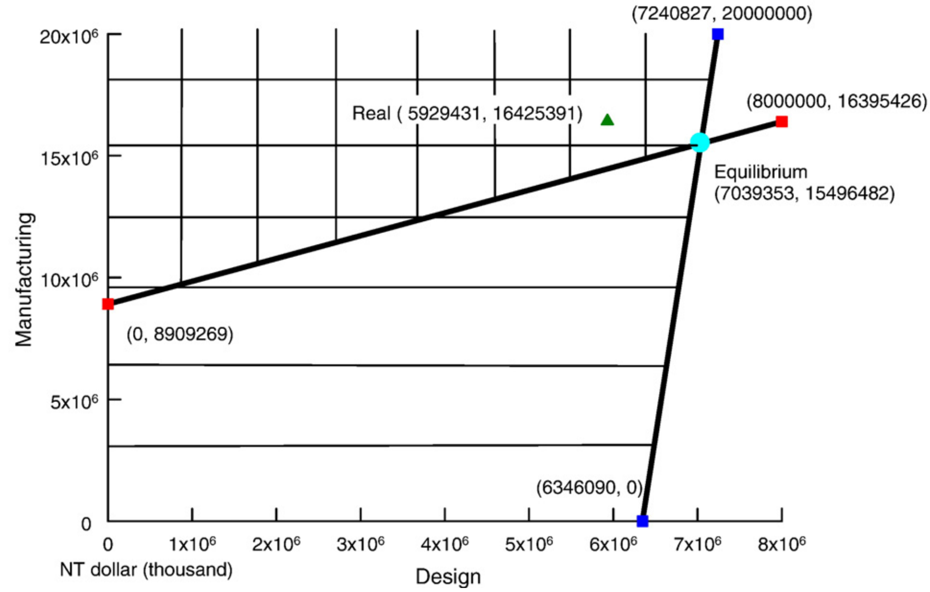

Fig. 8. Equilibrium point between IC design and IC manufacturing industries.

7039 millions, respectively). The capital inflows into China are still expanding for IC design industry, while shrinking for manufacturing industry.

When it comes to the relationship between the IC manufacturing and packaging-and-testing industries, the equilibrium point is shown in Fig. 9. The two straight lines developed in Eq. (11) intersect each other in the first quadrant, so these two series of FDI amount have an equilibrium point. From the coefficients, their equilibrium point is also proved to be stable according the balance conditions. The area with horizontal hatchings represents the region where the FDI amount of IC manufacturing industry will decrease ($dX/dt<0$), while the area marked with vertical hatchings represents the region where the amount of FDI of IC packaging-and-testing industry will increase ($dY/dt<0$). Hence, in the area with checkers, the amount of FDI of IC packaging-and-testing industries from Taiwan to China will increase, while the amount of FDI of IC manufacturing industries will decrease. As for the first quarter of 2008, the FDI amounts were 16,866 millions and 16,425 millions respectively for IC manufacturing and packaging-and-testing industries. That numbers correspond to a point in the area with checkers, and indicate that the two IC industries have not yet reached their equilibrium point (14,872 and 18,437 millions, respectively). IC packaging-and-testing industry will still expand its capital inflows, while manufacturing industry will reduce its FDIs.

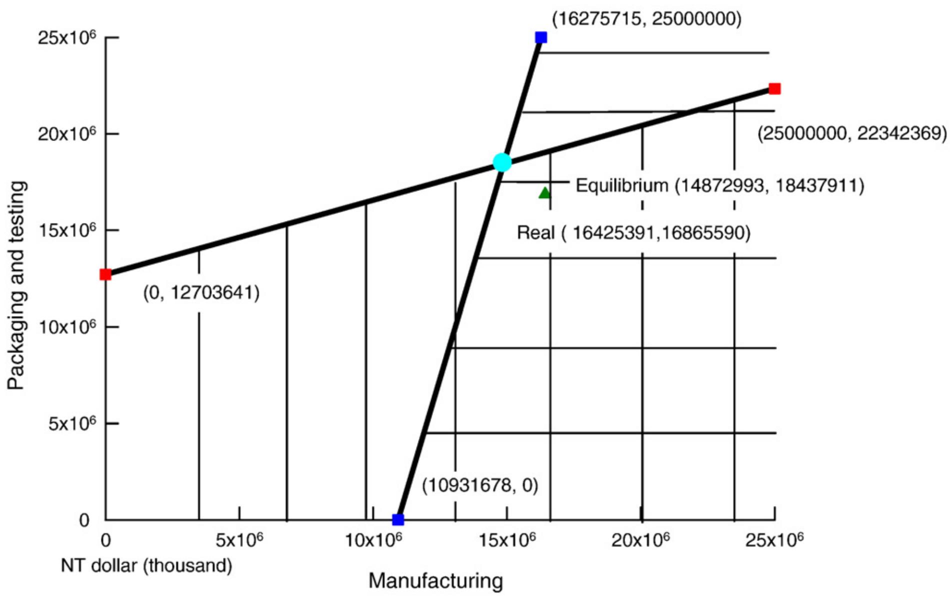

Fig. 9. Equilibrium point between IC packaging-and-testing and IC manufacturing industries.

From the equilibrium analysis, we can eventually conclude that FDI inflows into China are likely to rise for IC design or packaging-and-testing industry, while decline for manufacturing industry. In accordance with product life cycle theory [27], products are first introduced to a few developed countries and then onto the developing countries, so FDIs in emerging areas are kindled as the production process goes mature. Since this process is relatively low-end for IC packing and testing sector, the lower Chinese labor costs stimulate packaging-and-testing firms to engage in large amount of FDI in China. Taiwanese IC packaging-and-testing firms are therefore inclined to continue transferring their production into China where the labor wages are much lower than those in Taiwan. These IC packaging-and-testing firms obtain orders from manufacturing fabs all over the world and make use of the Chinese lower labor costs involved in basic packaging and testing activities. Empirical results are certainly consistent with product life cycle theory. In addition, IC design houses will continuously extend their branches in China, since more and more Chinese young people are well educated and make progress in research and development (R&D) skills.

In regards to IC manufacturing firms, it costs at least 3,000 million U.S. dollars to construct a 12-inch IC foundry fab and 2,400 million U.S. dollars on R&D to develop specific techniques for one single node along IC manufacture process. IC manufacturing industry is entirely a capital-intensive industry, so manufacturing firms engage in financing activities through large amount of bank loans and stock equity as they construct their factories and set up their equipments. These firms bear heavy burden of interest expenses and dividend costs after they finish building up their fabs and begin the operation. During the operation periods, if no sufficient manufacture orders are obtained in IC manufacturing firms, their sales revenues cannot afford such heavy costs of fab construction, interest expenses and dividend payment. Since no sufficient IC design firms located in China design electronics products and thus provide enough manufacture orders to such Taiwanese IC manufacturing firms located in China, these manufacturing firms have continuously suffered from the annual FDI losses from their first day of FDI into China to nowadays. In the future, their FDI amount in China ought to shrink to mitigate the burden of financing costs.

5. Conclusions

Prior research utilized Bass diffusion theory to analyze the industrial clustering evolutions when the industry is under vertical disintegration framework. However, the diffusion model can not effectively embody the industrial cluster evolutions since such model ignores the inter-level reciprocal interactions on the evolution process. For this reason, this paper focuses on Taiwan's IC industry whose framework belongs to vertical disintegration structure. The essential purpose of this article is to quantify the clustering formation from Taiwan to China among Taiwan's upstream IC design, midstream IC manufacturing as well as downstream IC packaging-and-testing industries by using FDI data.

In this paper, Lotka–Volterra model has been applied to investigate Taiwan's IC industry FDIs into China, with the explicit consideration of mutual dependence among Taiwan's IC design, IC manufacturing as well as IC packaging-and-testing industries. This work initially groups in pairs FDI values of the three industries: IC design, IC manufacturing, and IC packaging-and-testing industries. While the three FDI values are in turn grouped into three comparative pairs, Lotka–Volterra model is utilized to investigate the reciprocal influence among these three industries.

The results show that Taiwan IC industry's FDI amount into China is predicted to cumulatively increase, which supports the fact of industrial clustering tendency for Taiwan IC industry. The relationship between IC design and IC manufacturing industries or between IC design and IC packaging-and-testing industries exhibits a kind of commensalisms, in which the FDIs of IC manufacturing, packaging and testing industries are fundamentally driven by the FDI of IC design industry, while the FDI of IC design industry is hardly affected by IC manufacturing, packaging and testing industries. The results imply that IC manufacturing, packaging and testing industries would actively respond to the FDI decisions of IC design houses to undertake their FDIs since IC manufacturing, packaging and testing industries depend on IC design industry for advanced business benefits. If IC design houses move to China, IC manufacturing and IC packaging-and-testing houses would also cluster together into China.

It was also shown that Lotka–Volterra model is superior to Bass model in explicating the dynamics of IC clustering from Taiwan to China. The prediction capacity is dramatically revised and improved as the industrial mutualism among each IC production stage was taken into account. Furthermore, the equilibrium analysis has revealed that the dynamic equilibrium points exist for the three pairs of FDI series but these FDI flows have not yet reached equilibrium points for Taiwan's IC industry clustering into China. FDI inflows into China are likely to rise for IC design industry or IC packaging-and-testing industry, while decline in IC manufacturing industry. Consistent with product cycle theory, Taiwanese IC packaging-and-testing firms are inclined to continuously transfer their production into China to access the Chinese lower-wage labors. On the other hand, FDI amount of Taiwan's IC manufacturing firms has to be curtailed to minimize the continuous FDI losses in China nowadays.

The framework presented in this paper could be applied to other industrial clusters that contain mutual dependence at each level along the industrial value chain, and is expected to more accurately forecast the evolution process, which may pave a way for the establishment of more efficient FDI strategies or industrial policies. However, we have investigated clustering evolutions from Taiwan to China without considering the policy changes, of and between the Taiwanese and Chinese governments, which might be taken into account in the further research.

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