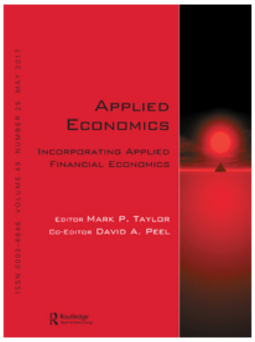

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Predicting the competitive relationships of industrial production between Taiwan and China using Lotka–Volterra model

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ABSTRACT

This work is the first to apply Lotka–Volterra model combined with genetic algorithm (GA) to predict the production relationships of high-tech industry among different areas. Previous studies analysed the trade interdependency among various countries, but few studies have highlighted the quantitative evidence of production relationships. Thus, this study utilizes motherboard shipment volumes to predict the competitive relationships of industrial production on both sides of the Taiwan Strait. Specifically, this work uses simultaneous non-linear least square regression in combination with GAs for numerical parameter optimization of the proposed Lotka–Volterra model. The results of parameter estimation reveal that shipment growth in China substantially promotes that in Taiwan, whereas the shipment growth in Taiwan curtails that in China. The standard deviation of the estimated parameters from the 3000 iterated simulations is small, confirming the reliability and stability of our parameter estimations. According to equilibrium analysis, the results of Lyapunov function prove that the shipments of China and Taiwan will reach a stable long-term equilibrium. The potential production from China will ultimately be nearly 16 times as large as that from Taiwan. Finally, the analytical results of forecast accuracy confirm that Lotka–Volterra model performs better than conventional *S*-curve diffusion model in predicting motherboard shipments.

KEYWORDS
Lotka–Volterra model; Lyapunov function; equilibrium analysis; forecast accuracy; China

JEL CLASSIFICATION
C53; L63; C62; R11

I. Introduction

This work is the first to apply Lotka–Volterra equations combined with genetic algorithm (GA) to interpret the production relationships between China and Taiwan and to utilize Lyapunov functions to predict their long-term equilibrium status in the computer-related industry. Taiwan was once the global manufacturing and export centre of electronic products and was the world leader in motherboard shipment volume. As manufacturing costs increased in Taiwan, order receptions stayed in Taiwan but the production sector shifted to China. The business models of electronic products, including motherboards, digital cameras, panels, semiconductors and mobile phones, have changed. Since 2005, China has overtaken Japan by becoming the largest trading partner of Taiwan (Sun and Chiu 2010). Consequently, the interdependency of trade between Taiwan and China is increasing, affecting the global electronics industry. However, previous studies focused more on the trade interdependency of products when analysing the economic relationship between China and Taiwan (Wang 2003; Xing 2012; Yeh and Ho 2012), and generally neglected manufacturing dependency. Additionally, previous studies failed to consider the competitive relationships of industrial production between China and Taiwan when predicting future shipment trends of China and Taiwan. This study investigates how production centres shifted from Taiwan to China by focusing on the intimate relationship of competition and cooperation between Taiwan and China in motherboard industries. The motherboard industry was among the first industries to shift production centres to China. The feature of a competitive–cooperative relationship, which exists in motherboard production across the Taiwan Strait, prevails in many high-tech industries. Thus, the findings of this study can serve as a valuable reference for strategy management in high-tech industries.

Regarding methodology, this work for the first time utilizes the Lotka–Volterra model to objectively

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quantify the competitive and cooperative relations of motherboard production between Taiwan and China. Most previous studies applied *S*-curve diffusion models to determine the market dynamics of durable products (Bass 1969). Shao (1999) studied the adoption of expert systems and utilized the diffusion models. Chien, Chen and Peng (2010) further modified diffusion model to forecast the diffusion of semiconductor product demand. However, these previous models excluded the analysis of reciprocal cooperation or competition among various production regions. If we apply the conventional diffusion model for a single species to explain the motherboard shipments of China and Taiwan, the estimation results may be biased. Thus, the first purpose of this study is to use the Lotka–Volterra model to consider these interactive effects and predict future motherboard shipments in China and Taiwan.

Previous studies on the Lotka–Volterra model, such as those by Tsai, Chang and Chang (2016), Tsai, Hsu and Balachandran (2013) or Tsai and Li (2011), typically use the Leslie (1958) discrete difference equation to indirectly estimate parameters in Lotka–Volterra models. The methodologies adopted in previous studies are unable to examine the statistical significance of the parameters, and thus, cannot demonstrate the statistical significance of competitive and cooperative relationships. To overcome this inability to perform statistical examination, the second purpose of this study is to apply GA, integrated with simultaneous nonlinear least square (NLS) estimation for unknown parameters in the numerical optimization of nonlinear differential equations. Our hybrid evolutionary and numerical optimization can be summarized in two steps: First, this work iterates GA simulations to randomly select different initial values. Because different initial value will result in different estimation of model parameters by NLS techniques, choosing a suitable initial value can help achieve better parameter optimization. To avoid an artificial manipulation of the initial value, this study used GA to randomly select 3000 sets of initial values. Second, this study employs the initial values from the first step to optimize parameters. The parameter optimization method is to iterate simultaneous NLS estimation until the optimized parameter could result in a predicted shipment value that generates errors smaller than the tolerable margin. Because this study uses 3000 GA iterations to obtain 3000 sets of initial values, so these 3000 sets of initial values are used to solve the Lotka–Volterra model by employing the simultaneous NLS method of Coleman and Li (1994, 1996). Based on these numerical parameter optimization procedures, we obtained 3000 sets of estimated parameters. This enables the use of *t*-statistics to examine the statistical significance of the competitive evolutionary process across various manufacturing regions and to identify estimated parameters within acceptable intervals.

The contributions of this work can be summarized in the following three aspects: model specification, parameter optimization and stability analysis of long-term equilibrium. Regarding model specification, this study is the first to utilize Lotka–Volterra model to investigate the evolutionary process of mainstream manufacturing centres of electronics and computer industries shifting from Taiwan to China. To estimate the motherboard shipment volume in China, the shipment volume in Taiwan is also be considered, and vice versa. Many studies have used the Lotka–Volterra model to describe the competitive interaction between two groups (Tsai, Hsu, and Balachandran 2013; Zhang 2012). Zhang (2012) states how China's institutional reforms are connected with the growth rate of private firms using a Lotka–Volterra model. The Lotka–Volterra model considers the self-diffusing evolution situation based on the traditional S-shape curve (Chien, Chen, and Peng 2010; Tsai 2013a) and includes competitive interaction between two groups (Tsai and Li 2009). In the production and sales of the high-tech manufacturing industry, Taiwan and China cooperate and yet compete with each other in the upstream and downstream sectors of the same supply chain. Therefore, our proposed Lotka–Volterra model can precisely predict shipment volumes for Chinese and Taiwanese high-tech industries, increasing the predictive accuracy of shipment quantity.

Referring to parameter optimization, this study for the first time employs GA combined with simultaneous NLS methods to undertake parameter optimization in Lotka–Volterra model. Binner et al. (2005) indicated that the most commonly used method to help the optimization algorithm to converge to a global minimum is to find the best local minimum or even the global minimum using GAs. Papadas and Hutchinson (2002) proposed that the structure of a backpropagation neural network using GAs will lead to improvements of the model forecast accuracy. Seppecher and Salle (2015) emphasize that GA incorporates a random selection process for solving the assortment problem. Relying on multipoint search and algorithmic features, GAs optimized initial values which converge to universal optimal solution instead of falling into local optimal solution. The advantage of adopting the GA approach in this work is to overcome the disadvantage in the conventional NLS method where optimization may not converge if the initial values are not relatively close to unknown parameter estimates. Based on these parameter optimization procedures of GA combined with simultaneous NLS in this research, the transnational impact that China and Taiwan motherboard shipments have on each other in the motherboard industry can be clarified.

As for stability analysis of long-term equilibrium, this study employs Lyapunov functions to determine the stability of the long-term equilibrium in motherboard production between China and Taiwan. The findings of equilibrium analysis highlight that the potential motherboard production from China is nearly 16 times as large as that from Taiwan. In addition, the stability results of Lyapunov functions confirm that Chinese and Taiwanese shipments will reach a stable equilibrium status and coexist until the market saturates. This suggests that Taiwan is not fully replaced by China in computer-related products, although the potential motherboard production in China eventually far exceeds that in Taiwan. Whether China replaces other countries in the manufacturing of computer-related products has attracted the attention in academic and practical fields. Thus, the application of Lyapunov functions in the stability examination of equilibrant production across different regions in our research can serve as a valuable reference for production locations decisions and strategic arrangements.

The rest of this article is organized as follows: Section II details background information. Section III introduces the parameter optimization method, forecast accuracy tests and equilibrium analysis of shipment volumes from Taiwan and China. Section IV presents a summary of the results of the parameter estimations, forecast accuracy tests and equilibrium analysis. Finally, Section V offers a conclusion and recommendations for future research.

II. Background

According to the statistics of the Market Intelligence and Consulting Institute (MIC), most motherboards in the world are manufactured in Taiwan and China. Feenstra and Hamilton (2006) indicated that motherboard industries worldwide have formed a powerful and complete supply chain. Taiwan has become the global motherboard production centre because of its advanced technology, consistent product quality and punctual shipments in high-tech industry (Tsai 2010). The MIC indicated that Taiwan's motherboard manufacturing industry was ranked first in shipment volume before 2004 because of continuous orders from companies worldwide. The Taiwanese motherboard manufacturing industry has long dominated the global market with a 50% market share, generating a noticeable effect on the entire industry.

However, the cost of production has gradually become increasingly crucial in the foundation of motherboard manufacturing centres in the past 10 years. According to location theory advanced by Smith (1981), corporations increase their competitiveness by situating their factories in regions with wide markets, cheap labour and a comprehensive basic infrastructure. Zhao and Zhu (2000) indicated that if market demand is large, a manufacturer's production volume can easily reach economies of scale. Summary and Summary (1995) also indicated that manufacturers aiming to maximize profits tend to invest in regions with the lowest costs, especially labour costs, in the value chain. Because of Chinese lower unit manufacturing costs, foreign manufacturers are inclined to establish subsidiaries to engage in production and sales in China with wide markets. Vernon's (1966) product life-cycle theory also emphasized that the manufacturing of a product that is innovated and launched in a developed country shifts to emerging countries as the manufacturing technology matures. Behaving in consistent with location theory and product life-cycle theory, many transnational companies have shifted their manufacturing centres to China in recent years for its low labour costs and great market demand.

This work accumulates the Chinese motherboard shipments since 2003 to depict the 'cumulative motherboard shipments' in Figure 1 and accumulate the investment amount of Taiwanese motherboard industry into China since 2000 to depict the 'cumulative investment amount from Taiwanese motherboard industry into China' in Figure 1. Figure 1 shows that the cumulative investment amount of Taiwanese motherboard industry increases from 34,329 million dollars in 2003 to 117,088 million in 2010. Taiwanese motherboard firms continuously set up factories and bring investment capitals into China. With the cheap labour, increased labour quality and vast markets, China is quickly becoming the world's largest factory. Consequently, the annual shipments of the Chinese motherboard increase from 108 million units in 2004 to 137 million units in 2007 (Figure 1). Although the annual motherboard shipment volumes decline during the European debt crisis, the annual motherboard shipments rebound after 2010. The cumulative motherboard shipments produced from China are over 900 million units up to 2010. From Figure 1, we can obviously observe the positive relationships between Chinese cumulative shipments of motherboards and cumulative investment amount of Taiwanese motherboard industry into China.

Chang et al. (2001) have proved the causal relationship of economic growth between Taiwan and Mainland China over the period from 1952 to 1995. Since 2005, China gradually replaced Taiwan as the largest motherboard-supplying country (Figure 2). With the supply expansion of motherboards from China, the average price of motherboards has decreased from \$61.3 US dollars in 2003 to \$46.72 US dollars in 2010, shrinking by 23.8%. This price

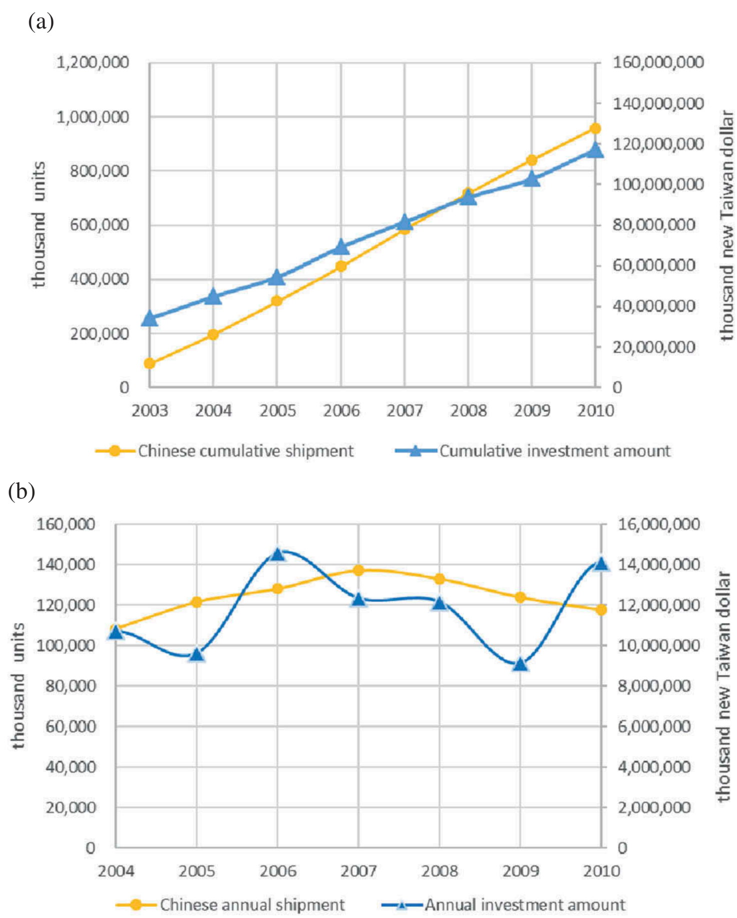

Figure 1. Relationships between Chinese cumulative motherboard shipments and cumulative investment amount from Taiwanese motherboard industry into China. (a) Cumulative investment amount of Taiwanese motherboard firms in China and Chinese cumulative motherboard shipments. (b) Annual investment amount of Taiwanese motherboard firms in China and Chinese annual motherboard shipments.

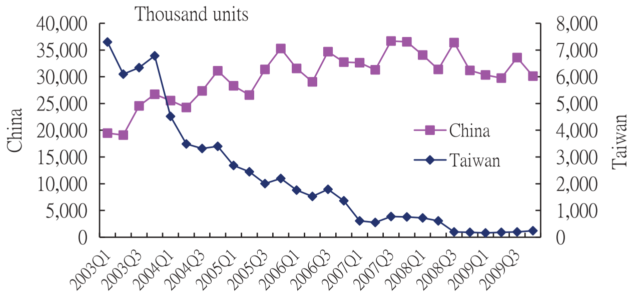

Figure 2. Motherboard shipments from China and Taiwan (in thousands of units).

decrease in motherboards crippled the profitability of global motherboard-manufacturing corporations. Especially after the financial crisis in 2008, the cost of raw materials and raw metals for the production of motherboards increased, forcing more foreign factories to relocate China to obtain cheaper labour. Thus, the global supply chains and business models of the worldwide motherboard industry must undertake strategic adjustments accordingly. Consequently, the manufacturing interactions between China and other areas, such as Taiwan, have become an important issue for industry, government and academia.

III. Methodology

Lotka–Volterra model

The Lotka–Volterra model uses the logistic equation and a term that accounts for the interaction with different species. The interaction between shipments volumes from the two production locations, Taiwan and China, can be expressed by the following two differential equations:

$$\frac{\mathrm{d}X}{\mathrm{d}t} = f_1(X,Y) = (a_1 - b_1X - c_1Y)X = a_1X - b_1X^2 - c_1XY, \quad (1)$$

and

$$\frac{\mathrm{d}Y}{\mathrm{d}t} = f_2(X,Y) = (a_2 - b_2Y - c_2X)Y = a_2Y - b_2Y^2 - c_2YX, \quad (2)$$

where $\mathrm{d}X/\mathrm{d}t$ and $\mathrm{d}Y/\mathrm{d}t$ denote the quarterly shipment volume of motherboard from China and Taiwan at each quarter t. X and Y are the cumulative shipment volume from China and Taiwan up to quarter t. $f_1(X,Y)$ and $f_2(X,Y)$ represent that $\frac{\mathrm{d}X}{\mathrm{d}t}$ and $\frac{\mathrm{d}Y}{\mathrm{d}t}$ are the functions of X and Y. The cumulative volume calculation starts with market entry of the motherboard manufacturer and accumulates quarterly until the fourth quarter of 2009. Additionally, X^2 and Y^2 refer to the same shipment interacting with itself, while XY and YX denote competing shipment interactions. Equations (1) and (2) contain all of the fundamental parameters that affect the growth rates of Taiwanese and Chinese motherboard shipments. Regional competition and cooperation can be determined through the parameters a_i, b_i and c_i. Parameter a_i represents the ability of China (or Taiwan) to multiply or grow its motherboard shipments by itself. The production in one region will stimulate the growth of its production, so this term a_i should have positive signs. Parameter b_i refers to the limitation parameter of China (or Taiwan), so the term b_i should be negative. Parameter c_i represents how Chinese and Taiwanese productions affect each other. When both c_1 and c_2 are positive, the relationship is classified as pure competition, a situation in which the shipments of both regions hurt each other's shipments. When both c_1 and c_2 are negative, the relationship is classified as mutualism, a symbiosis case or a win–win situation. When c_1 is positive and c_2 is negative, the relationship is classified as predator–prey, a situation in which one of them benefits the other. For the predator–prey relationship, the boom–bust cycle of different production sites, rather than the top-down relationships, controls motherboard shipments at equilibrium. From Figure 2, the boom–bust cycle patterns of Chinese and Taiwanese motherboard shipments correspond to the predator–prey trajectory in Lotka–Volterra models. It explains the appropriateness of our proposed Lotka–Volterra models in illustrating the production of different regions. Taiwanese motherboard industry dominated the motherboard production at first. After 2003, Taiwanese motherboard industry increasingly set up factories as well as transferred the motherboard production into China, so Taiwan and China are the early and emerging production sites, respectively. Early and emerging sites fight for the same sources of the motherboard production. Consider the case where the presence of the early production site has a negative influence on the growth of the emerging production site. Positive parameter c_1 represents the inhibitory effect that the early site production has on the growth of the emerging site production. In that case, the source of the growth for the early site production is proportional to its interactions with the emerging site production. Negative parameter c_2 represents the promoting effect that the emerging site production has on the growth of the early site production.

This work utilized the parameters a_i, b_i and c_i to examine how Chinese and Taiwanese motherboard shipments are related. The proposed Lotka–Volterra model forms a pair of non-linear differential equations, which are solved numerically using the GA approach combined with the simultaneous NLS method in order to optimize the parameters. The reason of adopting GA approach by this work is that the conventional NLS method, which uses a sequential search procedure to estimate parameter values in simulation programmes, requires initial values relatively close to unknown parameter estimates (Tsai 2013b); otherwise, optimization may not converge. Inadequate initial values can cause the method to converge to a local solution, rather than a global solution. To avoid inadequate initial values, this work attempts to optimize the non-linear ordinary differential equations of the proposed Lotka–Volterra models by using GAs to generate initial values for unknown parameters. GA is a global search procedure more capable of finding the best solution by searching from one population of solutions to another, while simultaneously sampling the total parameter space. Based on these parameter optimization procedures, the inter-industry impact that Chinese and Taiwanese motherboard shipments have on each other in the motherboard production is clarified.

Figure 3 shows a flow chart of the proposed computational procedure and investigation steps of our proposed hybrid evolutionary and numerical optimization approaches. Because different initial values will result in different estimation of model parameters using non-linear least square techniques, this study initially used GAs to randomly select 3000 different sets of initial values to avoid an artificial manipulation of the initial value. Next, the simultaneous NLS method is implemented to solve numerically the non-linear Equations (1) and (2). Once the computed solution is obtained, it is calibrated with real data to generate an accurate simulation. If the tolerance of the computational result exceeds that of an error, optimal parameters and results are obtained. Otherwise, a least squares optimization technique updates parameters for the next iteration. Through 3000 sets of initial values, the 3000 sets of estimated parameters a_i, b_i and c_i are allowed for the use of the t-statistics to examine directly the statistical significance of the competitive evolutionary process across various manufacturing areas and identify the estimated parameters located within acceptable intervals. Then, this work conducts the equilibrium analysis using Lyapunov function and investigates the forecast accuracy of our proposed Lotka–Voterra model.

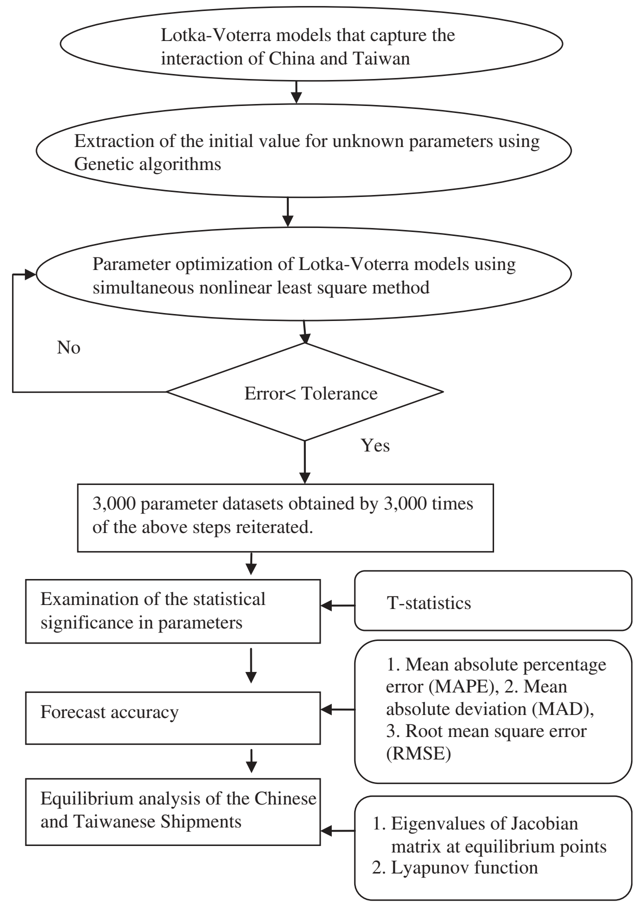

Figure 3. Flow chart of the computational procedure, simulation steps and equilibrium analysis.

Forecast accuracy

The Lotka–Volterra model in Equations (1) and (2) adds the competitive interactions between the motherboard shipments of China and Taiwan to conventional S-curve model. Previous study has extensively used the S-curve Bass (1969) model which does not take account of the competitors' interactions. To judge whether our proposed Lotka–Volterra model performs better than the conventional Bass model in predicting motherboard shipments of China and Taiwan, this work constructs the Bass model to compare forecast accuracy between Lotka–Volterra and Bass models. The quarterly shipment volume of motherboards in Bass model is expressed as the following equations:

$$\frac{dX}{dt} = (p_X + q_X X)(M_X - X), \tag{3}$$

$$\frac{dY}{dt} = (p_Y + q_Y Y)(M_Y - Y), \tag{4}$$

where $\frac{dX}{dt}$ and $\frac{dY}{dt}$ denote the quarterly shipment volume of motherboard from China and Taiwan at each quarter t. Also, X and Y are the cumulative shipment volume from China and Taiwan up to quarter t. This study follows Bass (1969) to estimate the parameters p_X, q_X, M_X, p_Y, q_Y and M_Y. M_X and M_Y are defined as potential production from China and Taiwan, respectively. After motherboard shipment volumes are estimated by Bass and Lotka–Volterra models using the training sample ranging from the first quarter of 2003 to the fourth quarter of 2009, the prediction accuracy of our proposed Lotka–Volterra model is compared with that of Bass model.

The ability of the Bass and Lotka–Volterra models to predict motherboard shipment growth is assessed. Parameters of both models are estimated using motherboard shipments from the first quarter of 2003 to the fourth quarter of 2009. Forecasted quarterly motherboard shipments from the first quarter of 2010 to the first quarter of 2011 are then compared with real quarterly shipments. Moreover, forecasting error is evaluated by mean absolute percentage error (MAPE), mean absolute deviation (MAD), and root mean square error (RMSE). The MAPEs are calculated as $MAPE = (1/n)\sum_{t=1}^{n} \left|(W_t - \hat{W}_t)/W_t\right|$; the MADs are calculated as $MAD = (1/n)\sum_{t=1}^{n} \left|W_t - \hat{W}_t\right|$ and RMSEs are calculated as $RMSE = \sqrt{\sum_{t=1}^{n} \left(W_t - \hat{W}\right)_t^2 / n}$, in which W_t is the actual shipment, $\hat{W}_t$ is the predicted shipment calculated by our proposed model.

Equilibrium analysis

Analysing the competitive relationship using the Lotka–Volterra model provides insight into the equilibrium state and illustrates the trajectory of change over time. In equilibrium, Equations (1) and (2) must equal zero because no simultaneous changes occur over time for each region. Thus,

$$\frac{dX}{dt} = 0 \quad \text{and} \quad \frac{dY}{dt} = 0. \tag{5}$$

Applying condition (5) to Equations (1) and (2) yields the following system of equations:

$$\begin{aligned} &a_1 X - b_1 X^2 - c_1 XY = X(a_1 - b_1 X - c_1 Y) = 0, \text{ and} \\ &a_2 Y - b_2 Y^2 - c_2 XY = Y(a_2 - b_2 Y - c_2 X) = 0 \end{aligned} \tag{6}$$

Solving Equation (6) yields

$$X = \frac{a_1 - c_1 Y}{b_1} \quad \text{and} \quad Y = \frac{a_2 - c_2 X}{b_2}. \tag{7}$$

The two lines, $dX/dt = 0$ and $dY/dt = 0$, cross each other, implying an equilibrium point. When the two straight lines in Equation (7) intersect in the first quadrant, the two systems of the motherboard shipment volumes are possible to reach equilibrium when shipment orbits comply with the stability conditions; otherwise, no equilibrium exists. This equilibrium point indicates that two motherboard manufacturing regions can coexist without dynamic changes.

Additionally, stability of the equilibrium point depends on parameter values in the proposed Lotka–Volterra model. By using those estimated parameters, this work examines whether these two pairs of cumulative shipment volume reach a stable equilibrium. This work employs the following two approaches to examine whether the final equilibrium point of both Chinese and Taiwanese shipment volumes are stable under the fluctuating environment: Eigenvalues of Jacobian matrix at equilibrium point and Lyapunov function.

Eigenvalues of Jacobian matrix at equilibrium point

This work chooses the equilibrium point on our trajectory to make linear approximation and then calculates the eigenvalues of the Jacobian matrix at the equilibrium point. For a linear system, $\dot{\mathbf{z}} = \mathbf{A}\mathbf{z}$, the Jacobian matrix at equilibrium point is:

$$\mathbf{A} = \left[\begin{array}{cc} \frac{\partial f_1}{\partial X} & \frac{\partial f_1}{\partial Y} \\ \frac{\partial f_2}{\partial X} & \frac{\partial f_2}{\partial Y} \end{array}\right]\Bigg|_{(X,Y)=(X^*,Y^*)} = \left[\begin{array}{cc} a_1 - 2b_1X - c_1Y & -c_1X \\ -c_2Y & a_2 - 2b_2Y - c_2X \end{array}\right]\Bigg|_{(X,Y)=(X^*,Y^*)} \quad (8)$$

where equilibrium point is (X^*, Y^*). Jacobian matrix $\mathbf{A}$ shows how every variable changes with each other variable at the equilibrium point. Hritonenko and Yatsenko (1999) indicate that equilibrium point satisfies the stability condition when both two real parts of the two eigenvalues are negative. If the equilibrium state is proven to be stable, the shipment trajectory reaches equilibrium point. Because the equilibrium point is the terminal point of Chinese and Taiwanese cumulative shipment trajectories, the stable equilibrium point illustrates the potential size of motherboard shipped by Taiwan or China. Restated, if the equilibrium status is stable, the motherboards are produced both from China and Taiwan until the market is saturated. Neither Taiwan nor China is expelled from the motherboard production because of each other.

Lyapunov function

Previous studies utilized Lyapunov theory to prove system stability (Nazemi and Effati 2013) and chose the origin as an equilibrium point for a linear system, $\dot{\mathbf{z}} = \mathbf{A}\mathbf{z}$, $\mathbf{z} \in R^n$ and $\mathbf{A} \in R^{n\times n}$. The equilibrium of the linear system is asymptotically stable if $\mathbf{P}, \mathbf{Q} \in R^{n\times n}$, $\forall \mathbf{Q} > 0$ and $\exists \mathbf{P} > 0$ exist and satisfy the Lyapunov function $\mathbf{A}^T\mathbf{P} + \mathbf{P}\mathbf{A} + \mathbf{Q} = 0$. Then, two conditions are held.

(i) $V(\mathbf{z})$ is locally positive semidefinite on the domain, namely, $V(\mathbf{z}) = \mathbf{z}^T\mathbf{P}\mathbf{z} \geq 0$,
(ii) the time derivative of the function $V(\mathbf{z})$ is locally negative semidefinite, namely, $\dot{V}(\mathbf{z}) = -\mathbf{z}^T\mathbf{Q}\mathbf{z} \leq 0$.

where matrices $\mathbf{P}$ and $\mathbf{Q}$ are systematic matrices. Because the matrix $\mathbf{Q}$ is required to be the positive definite and symmetric matrix, this work selects the unit matrix $\mathbf{I} \in R^{n\times n}$ as matrix $\mathbf{Q}$ in Lyapunov function. Incorporating the matrix $\mathbf{A}$ into Lyapunov function $\mathbf{A}^T\mathbf{P} + \mathbf{P}\mathbf{A} + \mathbf{Q} = 0$, the matrix $\mathbf{P}$ can be computed. To realize whether the equilibrium point in our Lotka–Volterra equations are asymptotically stable, this work examines the two aforementioned conditions, $V(\mathbf{z}) \geq 0$ and $\dot{V}(\mathbf{z}) \leq 0$ to judge the long-term stability of the equilibrant relations between Chinese and Taiwanese motherboard shipments. Since the equilibrium point is not on the origin, this work transforms equilibrium point (X^*, Y^*) as the new origin. Let the trajectory of our Lotka–Volterra model $X = X^* + X'$ and $Y = Y^* + Y'$. X' and Y' are new coordinate system. Then, $z' = (X', Y')^T$ is the trajectory of our Lotka–Voterra model after the coordinate transform. This work can examine whether $V(z') \geq 0$ and $\dot{V}(z') \leq 0$ to determine the stability of the equilibrium point (X^*, Y^*) for Chinese and Taiwanese motherboard shipments.

Data and sample

Quarterly global motherboard shipments are obtained from MIC databases. Because the shipment volume in the global motherboard manufacturing shipments has exceeded 115 million annually since 2003, we collect our sample from 2003. The study period lasts from the first quarter of 2003 to the first quarter of 2011, for a total of 33 quarters. As for our collected data, motherboards are shipped as three types: full system, barebone and pure motherboard. Full system refers to the type ready to be assembled as part of a brand computer. Barebone refers to a motherboard with a CPU and DRAM attached, without other computer parts. Pure motherboard refers to only the motherboard, without any computer parts. Motherboards in this study are defined as motherboards with gigabit Ethernet (GbE) LAN and graphics processing units (GPUs). The memory of the motherboard chipset should be able to support dual-channel DDR 400 and 800 MHz front-side buses. The GbE LAN on the motherboard can strengthen the computer's ability for massive data storage and transmission between computers. Conversely, GPU-embedded motherboards enable the computer to perform programmable shading. A motherboard equipped with these functions is capable of integrating its computing ability with the internet to undertake high-speed computing, massive transmission, and comprehensive display and storage. An external GbE network card or GPU card, or expansion of memory is unnecessary.

Motherboards that complied with this definition did not enter the market until 2003, marking the beginning of the data collected for our study.

This work divides our sample period into two periods: the in-sample period from the first quarter of 2003 to the fourth quarter of 2009 and the out-sample period from the first quarter of 2010 to the first quarter of 2011. Parameters of the proposed model are optimized using the data in the in-sample period, and the forecasting capabilities of different models are compared using the data in the out-sample period.

Table 1. The means and standard deviations of the estimated coefficients of the Lotka–Volterra model over 3000 iterations of motherboard shipment volumes in China and Taiwan.

	China		
	a_1	b_1	c_1
Mean	3.7575×10^{-1}***	1.6116×10^{-8}***	5.2121×10^{-6}***
Standard deviation	3.6353×10^{-8}	9.3202×10^{-9}	4.0924×10^{-7}
R^2	0.999618		
	Taiwan		
	a_2	b_2	c_2
Mean	4.1333×10^{-1}***	8.0997×10^{-6}***	-1.2271×10^{-7}***
Standard deviation	8.9816×10^{-9}	1.1496×10^{-7}	4.4198×10^{-9}
R^2	0.994502		

***Significant at the 1% level.

IV. Results and discussions

Competitive relationship analysis

The 3000 sets of estimated parameters were optimized using the shipment volumes of Chinese and Taiwanese motherboard industries from the first quarter of 2003 to the fourth quarter of 2009. The means and standard deviations of the 3000 sets of optimized parameters of the proposed Lotka–Volterra model are shown in Table 1. All 3000 sets of the estimated parameters a_i, b_i and c_i are approximate; therefore, the standard deviations of the 3000 sets of the estimated parameters are fairly small. Although the 3000 sets of the initial values are different, the optimized parameters are similar and stably located within a reasonable range. This finding suggests that our simulation involving the GA approach, which is combined with the simultaneous non-linear least squares method, generates stable and reliable parameters with only slight deviation.

According to the *t*-statistics results of Lotka–Volterra model, the statistical significance for the 3000 sets of estimated parameters are all maintained at a level of less than 1%. The self-effect parameters of Taiwan and China, b_i, are positive, indicating that both Chinese and Taiwanese motherboard shipments would compete among themselves in the same region. The more China (Taiwan) receives motherboard orders for production, the more they would crowd out the other region to manufacture motherboards. This suggests the severe saturation pressure existing within Chinese and Taiwanese motherboard industries. As shipment amount approaches market saturation, the growth rate of shipment decreases. In other words, the motherboard industry faces heavy internal rivalry within the same region.

We also noticed the b_1 in Taiwan is larger than that in China. It shows that a stronger inner self-squeezing pressure within Taiwan motherboard factories than Chinese motherboard factories. The amount of orders delegated to the Taiwanese factories is limited, leading to a strong competition and self-squeezing pressure for the Taiwanese factories. As one Taiwanese factory receives more order, others suffer from a decrease. Thus, Taiwan's annual growth rate in terms of market share does not compete with that of China.

On the other hand, the interaction parameter of the Chinese shipment volumes affected by Taiwan, c_1, is positive and significant, indicating that the Chinese shipment volume is squeezed by the massive stress of Taiwanese shipment volumes. The interaction parameter of the Taiwanese shipment volumes affected by China, c_2, is negative and significant, indicating that the Chinese shipment volume enhances Taiwanese shipment volumes. The results of c_1 and c_2 show that the predator–prey relationship exists between Taiwanese and Chinese motherboard industries. Obviously, Taiwan plays the role as predator and China as prey. Therefore, Chinese shipments volumes of motherboards will promote the shipment volumes of Taiwanese motherboards, while the shipment volumes from Taiwan will be curtailed by the shipment volumes from China. A possible explanation for this occurrence is that in motherboard manufacturing industry, most of the research and development of more advanced technology take place in Taiwan as opposed to China. New manufacturing technology of chipsets are developed in Taiwan and later transferred to China when the technology becomes mature. The shipments of Taiwanese motherboards will decrease the shipments of Chinese motherboards. On the other hand, motherboard orders from global computer firms are likely to request high-end motherboards to be manufactured in Taiwan during the sample period of our research. Because global computer firms, which send Original Equipment Manufacturer orders and Original Design Manufacturer orders to Taiwanese motherboard firms, worry the leakage of the core techniques and knowledge, these firms prohibited Taiwanese motherboard firms from producing high-end motherboards or chipsets in China. To meet the requirements of motherboard orders from these global computer firms, Taiwanese motherboard corporations manufactured motherboards numerously in their Chinese factories due to the low labour costs, but followed the contract to produce high-end motherboards in Taiwan. Especially, the Taiwanese motherboard firms remain research and design (R&D) activities of motherboards manufacturing through the surface-mount technology in Taiwan. Mass motherboard production in China promotes the growth of motherboard shipments in Taiwan. With respect to model fitness, the adjusted R^2 value of Lotka–Volterra model is very close to one during the in-sample period. This value shows the good fitness between simulated and actual shipment volumes. The interaction among Taiwanese and Chinese shipment volumes can be explained by using the proposed Lotka–Volterra model.

Results of forecast accuracy

This work then applies the average parameter values of the 3000 sets of optimized parameters in the proposed Lotka–Volterra model to calculate the simulated cumulative shipment volumes. Figures 4 and 5 depict the actual and simulated cumulative shipment volumes using the proposed Lotka–Volterra model and the Bass model for Chinese and Taiwanese shipments, respectively, in the in-sample and out-sample periods. Obviously, the forecasted volume is extremely close to the actual shipment volumes predicted by the proposed model. However, the predicted values of Bass model are far away from the actual cumulative motherboard shipments in China.

Table 2 summarizes the results of the model goodness and forecast accuracy in in-sample and out-samples, respectively. Analytical results indicate that MAPE of the simulated cumulative shipment volumes of the proposed Lotka–Volterra model are 2.9299% and 2.9932% for shipments volumes from China and Taiwan, respectively, during the in-sample period. Both MAPEs of these regions are lower than 5%. Notably, the proposed model correlates well with the actual shipments. Additionally, MAPE of the forecasted shipments of the proposed Lotka–Volterra model during the out-sample periods for Chinese and Taiwanese shipment volumes are 0.5493% and 1.9745%, respectively. Both MAPEs are also less than 5%. According to the criteria of Martin and Witt (1989), the predictive ability is

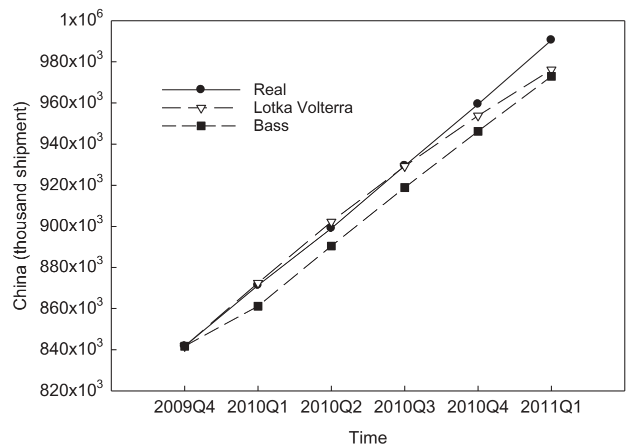

Figure 4. A comparison of actual cumulative shipment, simulated cumulative shipments from China using the Lotka–Volterra model and Bass model during the out-sample period (2010Q1–2011Q1).

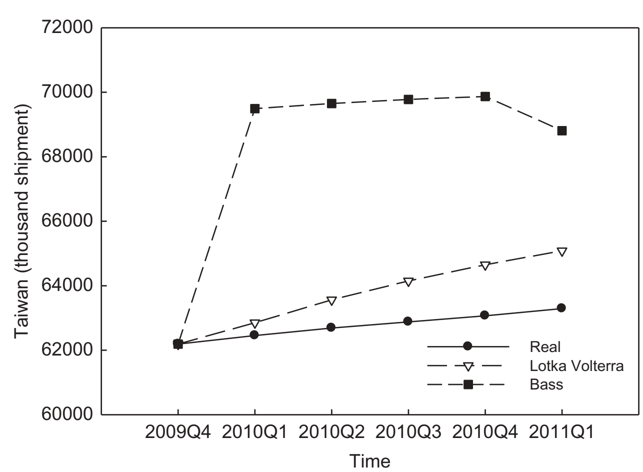

Figure 5. A comparison of actual cumulative shipment, simulated cumulative shipments from Taiwan using the Lotka–Volterra model and Bass model during the out-sample period (2010Q1–2011Q1).

Table 2. Comparison of forecast accuracy between Lotka–Volterra and Bass models in the out-sample and in-sample periods.

Out-sample	MAPE (%)	MAD	RMSE
Lotka–Volterra			
China	0.5493	5258.4641	191.1172
Taiwan	1.9745	1243.5127	1323.9461
Bass			
China	1.2813	12014.0548	12416.8626
Taiwan	10.5690	6643.5162	5516.5387
In-sample	**MAPE (%)**	**MAD**	**RMSE**
Lotka–Volterra			
China	2.9299	3197.6560	4695.1281
Taiwan	2.9932	895.0210	1199.7399
Bass			
China	3.2958	11142.9889	11862.1066
Taiwan	10.1500	5228.1809	5582.1820

excellent. Analytical results demonstrate the reliability of the proposed Lotka–Volterra model in predicting shipment performance. However, MAPE of the Bass model is nearly five times as large as that of Lotka–Volterra model for motherboard shipments in Taiwan during out-sample periods. The analytical results show that the forecast accuracy of Lotka–Volterra is superior to that of Bass model for predicting motherboard shipments.

Results of equilibrium analysis

The results of the eigenvalues of Jacobian matrix at the equilibrium point

Equilibrium analysis is performed by selecting the average values of parameters a_i, b_i and c_i to calculate the stability of the equilibrium point for Taiwanese and Chinese shipments. Eigenvalues of the Jacobian matrix at the equilibrium point in Equation (8) are −0.1408 and −0.4329. The analytical results of eigenvalues show that the shipment orbit computed by our estimated Lotka–Volterrra equations satisfies the Hritonenko and Yatsenko (1999) stability conditions, verifying the stability of the equilibrium point from Chinese and Taiwanese motherboard shipments.

Figure 6 shows the equilibrium point of Taiwanese and Chinese motherboards shipment volumes. Two linear functions for equilibrium are analysed by inputting the average values of a_i, b_i and c_i into Equation (7). The two straight lines in Equation (7) intersect each other in the first quadrant, indicating the existence of an equilibrium point for these two series of shipment volumes. Since the shipment orbits computed by our estimated Lotka–Volterra equations satisfy the Hritonenko and Yatsenko (1999) stability conditions, Chinese and Taiwanese factories continuously produce motherboard and these two shipments subsequently converge to their equilibrium point. Restated, the market diffusion for both should still expand to the equilibrium point.

Figure 6 depicts the trajectory of cumulative shipment volumes trajectory of Chinese and Taiwanese motherboard industries from 2003 to equilibrium point. According to Hritonenko and Yatsenko (1999), the area on the left side of line $dX/dt = 0$ in this figure represents the region where cumulative shipments increase from China ($dX/dt > 0$). Similarly, the area on the bottom side of line $dY/dt = 0$ represents the region where Taiwanese cumulative shipments increase ($dY/dt > 0$). For the fourth quarter of 2009, 841,735 and 62,188 thousand pieces of motherboards were shipped by China and Taiwan, respectively. Those numbers correspond to a point where the two manufacturing production areas have not yet reached their equilibrium point, 1154,586 and 68,523 thousand pieces for Chinese and Taiwanese motherboard shipments, respectively. Because this work demonstrated the stability of the equilibrium point, the cumulative shipment trajectory would still expand after 2009 and eventually converges to the equilibrium point. Before reaching the equilibrium point, motherboards shipments extend at higher speed in China than in Taiwan after 2009, since Taiwanese motherboard manufacturing firms continuously set up factories in China and the total cumulative investment amount from

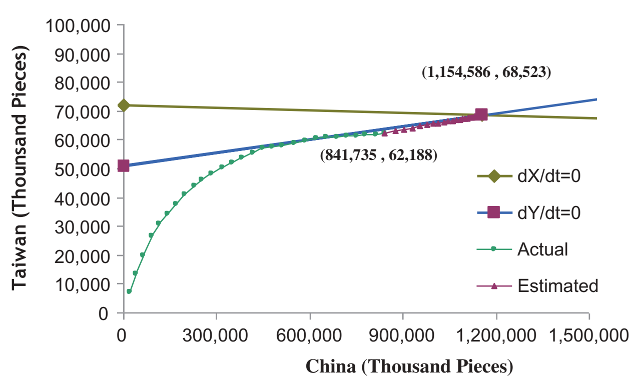

Figure 6. Phase diagram for the cumulative shipment trajectory of Chinese and Taiwanese motherboard industries from 2003 to equilibrium point.

Taiwan into China increases from 8855 million in 2000 to 126,773 million in 2011 (Figure 1). Taiwan persistently transferred the motherboard production into China.

The results of Lyapunov analysis

Referring to the Lyapunov stability equilibrium analysis, this study transforms the equilibrium point as the new origin on the coordinate axis. By way of the coordinate transformation, a calculated point on the trajectory, 1081,972 and 67,092 thousand pieces from China and Taiwan, is noted in the new coordinate system as $\mathbf{z} = (u, v) = (-72{,}613, -1431)$. Incorporating the Jacobian $\mathbf{A}$ into Lyapunov function and $\mathbf{Q} = \mathbf{I},\ \mathbf{I} \subset R^{n\times n}$, this work computes $\mathbf{P} = \begin{bmatrix} 5.2798 & -47.7822 \\ -47.7822 & 518.9788 \end{bmatrix}$ and further calculates $V(\mathbf{z}') = 1.897 \times 10^{10} > 0,\ \dot{V}(\mathbf{z}') = -5.275 \times 10^{9} < 0$, proving that the trajectory satisfies the stable conditions of its equilibrium point, and will at last converge to equilibrium point, 1154,586 and 68,523 thousand pieces from China and Taiwan. From the parameter estimation results, the boom–bust cycle of the early and emerging production sites, rather than the top-down relationships, controls Taiwanese and Chinese motherboards at equilibrium.

Even now, neither China nor Taiwan shipment has reached market saturation. As is expected, both of them eventually achieve stable market potential equilibrium around 2018, 1154,586 and 68,523 thousand pieces from China and Taiwan, respectively. We can infer from the equilibrium point that the potential production from China (1154,586 thousand pieces) is nearly 16 times as large as that from Taiwan (68,523 thousand pieces). As the technologies of motherboard manufactures mature, motherboard enterprises are searching to build factories in China to manufacture motherboards, thus reducing the cost of operating factories. Particularly, due to the series of global financial crises subsequent to Lehman Brothers bankruptcy in 2008, consumers are more sensitive to product prices. In order to increase the profitability and to reduce labour cost, the production of motherboard is even more centralized in China, resulting in a much larger shipment volume increase in China than in Taiwan. The formidable supply chain constructed by the global electronic industry after 2000 can develop the economies of scale, enhance product quality, as well as decrease product price by mass production, explaining why consumers can afford and prefer products produced in China more than before. Consequently, Chinese factories dominate the production in the motherboard manufacturing sector. Motherboard industry immigrates production site from Taiwan to China, providing more job opportunities in China. On the other hand, the labour demand for motherboard production has decreased substantially in Taiwan. Since Taiwan did not successfully change the industrial structure and upgrade the technology skills, the production immigration from Taiwan to China has increased the unemployment rate and has decreased gross domestic products of Taiwan in recent years. Taiwan suffers severe economic challenges due to the low indigenous production.

V. Conclusions

This study used the Lotka–Volterra model to investigate global motherboard shipments and considered the interactive dependence among various production regions in the motherboard industry. Specifically, how production centres shifted from Taiwan to China is explored by focusing on the intimate relationship of competition and cooperation between motherboard industries in Taiwan and China. Empirical results of this investigation show that the Lotka–Volterra model can be used to determine the reciprocal influence among shipments of these two production regions in the motherboard industry.

Analytical results demonstrate that Chinese shipment volumes of motherboards promote the shipment volumes of Taiwanese motherboards, whereas shipment volumes from Taiwan curtail those from China. A possible explanation for this phenomenon is that, in the motherboard manufacturing industry, most R&D of more advanced technologies occurs in Taiwan. New chipset manufacturing technologies are developed in Taiwan and subsequently transferred to China when the technology matures. Thus, the shipment of Taiwanese motherboards reduces that of Chinese motherboards. Conversely, motherboard production in China often stipulates that a specific proportion be manufactured in Taiwan. Therefore, an increase in Chinese motherboard demands not only encourages shipments from China, but also promotes shipments from Taiwan. In addition, the investigation results of the Lyapunov function show that the trajectory of the predicted motherboard shipments fulfils the stable conditions of the equilibrium point, and finally converges to an equilibrium point. According to the long-term prediction of our equilibrium analysis, the potential motherboard shipment from China, will ultimately be 16 times as large as that from Taiwan, although Taiwan used to be the largest exporter of motherboard. This suggests a transnational production shift from Taiwan to China in computer industry. Finally, the Lotka–Volterra model performs well in fitness and forecast accuracy because it considers the competitive relationships between Chinese and Taiwanese shipments, which conforms to the manufacturing practices.

We developed a novel Lotka–Volterra model that allows academics and practitioners to better understand the production interaction across different regions beyond what was possible in previous methods. The proposed predictive model represents a major step forward in the fields of model-base management system, information management, technological forecasting and management science, highlighted by the following four aspects: unique data, model specification, parameter optimization, and applicability to industrial analysis. In reference to unique data, the novel Lotka–Volterra model uses shipments from China and Taiwan as quantitative indicators for measuring the interactions between various production regions. Most studies in decision science lack quantitative data to state the production dependency across Taiwan Strait, so our unique data were utilized to quantify the collaborations among different regions.

Referring to model specifications, this study is the first to construct a model that incorporates interactive relationships among various regions. Based on the results of this study, we suggest that Chinese and Taiwanese shipments in the motherboard industry coexist in a relationship of competition and cooperation. Unlike the conventional Bass model used in previous research (Hujala and Hilmola 2009; Girifalco 1991), the proposed method eliminated the restrictive assumption that Chinese and Taiwanese productions are unrelated. The specifications of the proposed model are more in line with reality compared to the conventional Bass model.

In terms of parameter optimization, the proposed method combines GAs and simultaneous NLS to numerically optimize parameters. This approach avoids the shortcomings of previous studies, which used conventional NLS methods. In previous studies, poor initial values converged to a local, instead of a global solution. The empirical results of this study demonstrate that the standard deviation of the estimated parameters is small, confirming that the optimized parameters remain similar, despite our GA simulations having used 3000 different sets of initial values. This finding shows that the proposed approach generates stable and reliable parameters, with little deviation.

As for the applicability of this approach to technological forecasting, the results of equilibrium analysis show that China, the major production region of motherboards, has greater market potential than Taiwan in the long run. Previous studies have failed to quantitatively demonstrate the stable long-term coexistence of Chinese and Taiwanese factories. The current predictive results provide managerial implications for interdependence among various production regions in high-tech industries. The proposed equilibrium analysis can be used to predict the competition of various production regions in other high-tech industries, including those of TFT-LCDs, computers, communications, information technology and consumer electronics.

The proposed framework of this study can be applied to state the relations among various production regions that contain manufacturing dependence, and it can be used to accurately forecast the evolution process of products. This approach paves the way for the establishment of efficient product marketing and production policies. However, the Lotka–Volterra model assumes linear relations between Taiwanese and Chinese motherboard shipments, so each Taiwanese motherboard production curtails a constant proportion of the Chinese motherboard production regardless of their density. In addition, the motherboard shipments of Taiwan and China are assumed to be affected without time lag in our proposed Lotka–Volterra model. These impractical assumptions may lead to the limitations of our proposed Lotka–Volterra model. In addition, the European debt crisis may have adversely affected the future markets of motherboards and other technological commodities. Thus, future research should specify the potential market size as a function of macroeconomic factors for any financial crisis.

Furthermore, future studies should consider financial crises when adopting the Lotka–Volterra numerical simulation method to compute the parameters of product diffusion. This will allow the models to better reflect the actual occurrence.

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Disclosure statement

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