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FORECASTING IC DESIGN INDUSTRIAL CLUSTERING FROM TAIWAN TO MAINLAND OF CHINA USING FOUR-DIMENSIONAL COMPETITIVE LOTKA-VOLTERRA EQUATIONS

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Abstract. *This investigation is the first to use four-dimensional Lotka-Volterra equations, to elucidate the clustering process of integrated circuit (IC) design firms from Taiwan to Mainland of China. Our four-dimensional Latke-Volterra equations express not only the word-of-mouth effect but also the impact of Chinese balanced regional policies in location selections. This study further conducts the accuracy analysis of our proposed four-dimensional models and the Bass model in predicting the clustering evolutions from Taiwan to Mainland of China. The parameter results of the Lotka-Volterra equations show that the word-of-mouth effect of the incumbent firms, which have previously undertaken direct investment in Mainland of China at an earlier time, attract successive firms to invest in North, South, and Mid-west China. However, the governmental balanced regional development policies dominate the industrial clustering evolutions of Mid-west China. The increase in operational costs in South China enhances Taiwan's IC design firms to set up new branches in Mid-west China where Chinese balanced regional development policies provide preferential treatment to foreign enterprises. Because our proposed four-dimensional models consider the regional transformation of industrial clusters caused by the Chinese balanced regional development policies, our proposed models outperform the Bass model in predicting the clustering evolutions from Taiwan's IC industry into Mainland of China.*

Keywords: Balanced regional development, Industrial cluster, Location theory, Word-of-mouth, Accuracy analysis

1. **Introduction.** This investigation is the first to use four-dimensional Lotka-Volterra equations to examine the clustering of Taiwan integrated circuit (IC) design companies in Mainland of China due to the close relationships between Taiwan and Mainland of China [1-3]. Li et al. [4] state that bilateral trade attracts foreign direct investment in Mainland of China. Previous research illustrates how Taiwanese businesses expanded factories in Mainland of China under the pressure of increasing Taiwan's wages and formed industrial clusters in various Chinese regions [5]. Huang and Wei [6] show that agglomeration economies, transportation facilities, and public environments in Chinese industrial clusters are essential for attracting foreign direct investment to build factories in Mainland of China. Zeng et al. [7] state how the Chinese Zhangjiang high-tech parks attract foreign IC firms to form an industrial cluster there. Because IC design industrial clusters play an important role in high-tech industrial development, it is critical to elucidate what factors dominate the IC design industrial cluster formation in each Chinese region.

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Most investigations of industrial clustering are qualitative; they tend not to take a quantitative approach because either data or evidence elucidating industrial clustering is not easy to find [8]. To solve this problem, our investigation uses accounting statements that disclose the amount of investment made by individual Taiwanese firms in Mainland of China. This study uses the capital investments made by Taiwanese firms in facilities in Chinese regions as a proxy for the sizes of an industrial cluster. As Taiwan's IC companies have expanded into Mainland of China by investing in production or operational facilities, the amount of investment in Mainland of China has increased, causing industrial clusters in Mainland of China to expand. The amount that has been invested by Taiwanese companies in Mainland of China is a reliable measure of the extent to which industrial clusters from Taiwan have expanded into Mainland of China. Because the value of the sales made by Taiwan's IC manufacturing and design industries has respectively ranked top one and two globally since 2004, Taiwan's IC industry's westward strategy gradually transforms the global IC center into Mainland of China.

Cui and Liu [9] emphasized the diversity among Chinese regions, such that industrial clustering in each Chinese region is a critical aspect of a decision to invest in Mainland of China. Thus, it is important to explore what factors dominate the evolutions of the Taiwanese IC design industry toward investing and forming IC design clusters in North, East, South, and Mid-west China. Literature on location theory has demonstrated that overseas investment depends on the advantages available in the area [10]. These studies explain the location chosen from the perspectives of scale economies, localization economies, and urbanization economies. The interactions among economies of scale, transportation cost and mobility are the major factors of location choice [11]. Chen and Tsai [12] state that corporations should be located by minimizing the cost. In addition, Hecht [13], Gammeltoft and Hobdari [14], and Schäffler et al. [15] further state that locating within the industrial district stimulates innovation. Hsieh et al. [16] study the industrial cluster theory on service innovation for providing higher perceived service values to customers to increase competitive advantage. The cited studies imply that industrial cluster formation is closely related to location advantages such as cost reduction, profitability and public facilities advantages. Demir and Su [17] and Bojnec and Fertő [18] emphasize that the relaxation of entry barriers and globalization enhance foreign direct investment. The first purpose of this study is to examine whether the word-of-mouth of the incumbent firms, which have previously undertaken direct investment in North, South, and East China at an earlier time, attract successive firms to invest in North, South East and Mid-west China.

On the other hand, Mid-west China which lacks location advantages depends on governmental balanced regional development policies to form industrial cluster evolutions. Andriesse [19] emphasizes that the Philippines' regional disparities rely on the governmental policies of balanced regional development to transfer resources, capital investment, and public services to poor regions. To deal with the regional inequalities, the Chinese central government and Mid-west China municipal government implement balanced regional development policies to provide income tax exemption, income tax reduction, venture funds, and start-up subsidies for foreign enterprises which set up factories in Mid-west China. The formation of Taiwan's IC clusters in Mid-west China is likely to be affected by Chinese balanced regional development policies. Political interference has long played an important role in economic development [20]. Regarding poor Mid-west China where the governmental tax exemptions are implemented on the foreign direct investors under the Chinese 11th five-year plan, the second purpose of our study is to ascertain whether these balanced regional policies expand the industrial clusters of Taiwanese IC design firms in Mid-west China.

Numerous investigations have used the conventional two-dimensional Lotka-Volterra model to describe competitive interactions between two groups [21,22]. The two-dimensional Lotka-Volterra model in previous studies cannot be applied to industrial clustering transformation from other regions to Mid-west China caused by Mainland of China's balanced regional development policies. To overcome this drawback of conventional two-dimensional Lotka-Volterra model, this work is the first to construct four-dimensional Lotka-Volterra equations to consider the regional transformation of industrial clustering due to the governmental policies of balanced regional development. This study uses a statistical methodology to elucidate the interactive relationships among industrial clusters in North, East, South, and Mid-west China where Taiwanese companies form IC industrial clusters. Finally, the third purpose of this work is to compare the actual value and our predicted value proposed by the four-dimensional Lotka-Volterra model using the criteria of accuracy rate in previous research [23]. Furthermore, the conventional Bass [24] model, which ignores the inter-region interactions resulting from the balancing economy policies, is constructed to interpret the IC clustering from Taiwan to North, East, South, and Mid-west China. We compare the forecast accuracy between our proposed four-dimensional Lotka-Volterra model and the Bass model. This paper is organized as follows. In Section 2, we propose the methodology. In Section 3, we define the data and sample. As for Section 4, we discuss the empirical results. Finally, we draw conclusions in Section 5.

2. **Methodology.**

2.1. **Four-dimensional Lotka-Volterra equations.**

This study constructs four-dimensional Lotka-Volterra equations to analyze Taiwanese IC design companies' investments in four different regions of Mainland of China: North, East, South and Mid-west China. The four-dimensional Lotka-Volterra equations can be expressed by four differential equations (Equations (1)-(4)):

$$\frac{dX_1}{dt} = a_1X_1 + c_{11}X_1^2 + c_{12}X_1X_2 + c_{13}X_1X_3 + c_{14}X_1X_4 \tag{1}$$

$$\frac{dX_2}{dt} = a_2X_2 + c_{22}X_2^2 + c_{21}X_2X_1 + c_{23}X_2X_3 + c_{24}X_2X_4 \tag{2}$$

$$\frac{dX_3}{dt} = a_3X_3 + c_{33}X_3^2 + c_{31}X_3X_1 + c_{32}X_3X_2 + c_{34}X_3X_4 \tag{3}$$

$$\frac{dX_4}{dt} = a_4X_4 + c_{44}X_4^2 + c_{41}X_4X_1 + c_{42}X_4X_2 + c_{43}X_4X_3 \tag{4}$$

where X_1, X_2, X_3, and X_4 are the cumulative amount of Taiwan IC design industries invested in the North China, East China, South China, and Mid-west China regions. Each region has its own sets of parameters a_i, c_{ii}, and c_{ij} to explain the way that word-of-mouth, intra-regional and inter-regional effects influence the change of cumulative investment amount of individual regions, respectively. The first set of intra-industry imitation parameter a_i describes how experienced IC design firms, which have invested in the Chinese regions, attract successive firms to spontaneously extend their divisions within the same region. Positive parameter a_i denotes the word-of-mouth driven by the incumbent Taiwan IC design firms. Conversely, negative parameter a_i denotes bad word-of-mouth, which deters the growth of the industrial clusters. The second set of parameters c_{ii} accounts for the intra-specific effect within the same region. The positive parameter c_{ii} represents the intra-specific interference that restrains Taiwanese IC design firms from continuously investing within the region where more and more IC design firms set up factories. The third set of parameters c_{ij} represents the inter-regional effect from the other three different regions. The sign c_{ij} represents the competition type or relationship

between any two regions in this study. Negative c_{ij} represents the situation in which the investment size of one region depresses the size of another region. Positive c_{ij} represents a situation in which the investment size of Taiwanese IC design firms in one region enhances the investment size of another region. The sizes of Taiwan's IC design industrial cluster in North China, East China, South China, and Mid-west China regions are assumed here to correspond to their cumulative investment amount to these four areas. This work utilizes the inter-specific parameter c_{ij} to determine whether competition or cooperation exists among the four industrial clusters of Taiwanese IC design firms in North China, East China, South China and Mid-west China regions.

The four-dimensional Lotka-Volterra equations in Equations (1)-(4) are continuous models. However, this study will use discrete time series data, so the continuous four-dimensional Lotka-Volterra equations must be converted to discrete time series models for parameter estimations. Liu and Gopalsamy [25] find and develop the multiple-dimensional Lotka-Volterra model which will be adopted for this study:

$$X_1(t+1) = \frac{\alpha_1 X_1(t)}{1 + \beta_1 X_1(t) + \sum_{j\neq 1} \gamma_{1j} X_j(t)} \tag{5}$$

$$X_2(t+1) = \frac{\alpha_2 X_2(t)}{1 + \beta_2 X_2(t) + \sum_{j\neq 2} \gamma_{2j} X_j(t)} \tag{6}$$

$$X_3(t+1) = \frac{\alpha_3 X_3(t)}{1 + \beta_3 X_3(t) + \sum_{j\neq 3} \gamma_{3j} X_j(t)} \tag{7}$$

$$X_4(t+1) = \frac{\alpha_4 X_4(t)}{1 + \beta_4 X_4(t) + \sum_{j\neq 4} \gamma_{4j} X_j(t)}, \quad j = 1, 2, 3, 4 \tag{8}$$

In Equations (5)-(8), α_i and β_i are the influence parameters for logistic growth within the same region. The word-of-mouth parameter a_i can be calculated from α_i. The parameter γ_{ij} accounts for the interaction influence to region i by region j. The parameters have a relationship as the following equations:

$$a_i = \ln \alpha_i \tag{9}$$

$$c_{ii} = \frac{\beta_i a_i}{1 - \alpha_i} = \frac{\beta_i \ln \alpha_i}{1 - \alpha_i} \tag{10}$$

$$c_{ij} = \gamma_{ij} \frac{c_{ii}}{\beta_i} = \frac{\gamma_{ij} \ln \alpha_i}{1 - \alpha_i} \tag{11}$$

2.2. **Forecast accuracy.** Li et al. [26] and Li et al. [27] evaluate the forecast performance using the accuracy rate. This study follows Li et al. [26] and Li et al. [27] to evaluate the forecast performance of the four-dimensional Lotka-Volterra equations used in this study, and we will try to compare its prediction performance with conventional Bass diffusion model. The Bass diffusion model with constant coefficients is as the following:

$$\Delta Y_t = \theta_1 + \theta_2 Y_{t-1} + \theta_3 Y_{t-1}^2 + e \tag{12}$$

where, in this study, Y_{t-1} represents the cumulative amount of investment at time $t-1$, and ΔY_t denotes the investment growth between interval $(t-1, t)$. The word-of-mouth parameter θ_2 describes how experienced IC design firms, which have invested in the Chinese regions, attract successive firms to spontaneously extend their divisions within the same region. The intra-regional parameter θ_3 accounts for the intra-specific effect within the same region when industrial clusters of Taiwan IC design firms continue to expand in this region where resources are limited. Equation (12) exhibits that the Bass model lacks the

interaction terms of different regions, so the difference between Bass and four-dimensional Lotka-Volterra equations is that the Bass model lacks considering the inter-regional effect.

To determine the forecast performance of our proposed four-dimensional Lotka-Volterra equations and the Bass diffusion model, this study uses the mean absolute percentage error (MAPE) method to compare the actual quarterly amounts with the values predicted by four-dimensional Lotka-Volterra equations or conventional Bass model. The MAPE equation is shown in Equation (13):

$$\text{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{Y_i - \hat{Y}_i}{Y_i}\right| \tag{13}$$

where Y_i is the actual value and $\hat{Y}_i$ is the forecast value. Martin and Witt [28] classify predictive ability into four levels. The forecasting capacity of a model is "excellent" as MAPE is smaller than 10% (MAPE $< 10\%$). Forecasting capacity is "good" as MAPE locates in the interval $[10\%, 20\%]$ ($10\% <$ MAPE $< 20\%$). Forecasting capacity is "reasonable" as MAPE is in the interval $[20\%, 50\%]$ ($20\% <$ MAPE $< 50\%$). In addition, the study also uses the statistical result of adjusted R^2 to evaluate the fitness of the model adoption. The value of adjusted R^2 close to the value "one" represents a good overall explanation of the examined model.

3. **Data and Sample.** This work collects real data covering 78 Taiwanese IC design firms, of which 33 are involved in cumulative investment in East China, 30 in South China, 7 in North China, and 8 in Mid-west China. The Mid-west China is defined as the region covering the Central China, Southwest China, and Northwest China. This work obtains quarterly data on cumulative investment amounts from the first quarter of 2003 to the first quarter of 2023. The sample data are divided into two parts, the training sample, and the test sample. The four-dimensional Lotka-Volterra equations and conventional Bass model use the training sample, ranging from the first quarter of 2003 to the fourth quarter of 2020 to develop two different prediction models. The accuracy of both the conventional Bass and our four-dimensional Lotka-Volterra equations is evaluated by comparing the predicted values with the actual value in the test period collected from the first quarter of 2021 to the first quarter of 2023. These sample data are collected from the *Taiwan Economic Journal* database. The net investment into Mainland of China is defined as the amount of investment in Mainland of China minus the amount of investment returned to Taiwan. The cumulative investment amount may decrease if the amount of investment returned to Taiwan exceeds the amount flowing into Chinese areas. This research uses the cumulative investment amount of Taiwan IC design firms in North, East, South and Mid-west China as the industrial cluster criteria since Jensen [29] emphasizes that direct investment in factories generates industrial cluster constructions.

4. **Empirical Results.**

4.1. **The results of parameter estimation.** Table 1 shows the estimated parameters of each region derived from the discrete-time Lotka-Volterra equations from Equations (5) to (8) and continuous Lotka-Volterra equations from Equations (1) to (4). The coefficients, α_i of North, East, South, and Mid-west China, are all significantly positive and more than one. Using Equations (9) to (11), we can calculate the positive word-of-mouth coefficient a_i for North, South and Mid-west China in continuous four-dimensional Lotka-Volterra equations. The positive word-of-mouth coefficient implies that these regions are well-equipped with the conditions for developing the IC industry and related information technology industrial clusters. The advantages of industrial clusters attracted Taiwanese

TABLE 1. The estimated parameters of discrete-time and continuous four-dimensional Lotka-Volterra equations

	Discrete-time (Equations (5)-(8))			Continuous (Equations (1)-(4))		
Region	Parameter	t-statistics		Influence		Parameter
North	α_1 1.6330	7.250	***	a_1	Word of mouth	4.9041×10^{-1}
	β_1 2.6351×10^{-7}	3.480	***	c_{11}	Intra-regional	-2.0416×10^{-7}
	γ_{12} 1.0587×10^{-9}	0.066		c_{12}	East	-8.2021×10^{-10}
	γ_{13} -2.3075×10^{-8}	-0.514		c_{13}	South	1.7878×10^{-8}
	γ_{14} -7.5635×10^{-8}	-0.737		c_{14}	Mid-west	5.8599×10^{-8}
East	α_2 9.7934×10^{-1}	15.969	***	a_2	Word of mouth	-2.0878×10^{-2}
	β_2 9.1954×10^{-9}	2.304	**	c_{22}	Intra-regional	-9.2918×10^{-9}
	γ_{21} -2.8794×10^{-8}	-1.779	*	c_{21}	North	2.9095×10^{-8}
	γ_{23} -2.6915×10^{-8}	-2.069	**	c_{23}	South	2.7197×10^{-8}
	γ_{24} 5.2516×10^{-8}	1.558		c_{24}	Mid-west	-5.3066×10^{-8}
South	α_3 1.0956	27.528	***	a_3	Word of mouth	9.1265×10^{-2}
	β_3 1.3417×10^{-8}	1.458		c_{33}	Intra-regional	-1.2814×10^{-8}
	γ_{31} 9.3255×10^{-11}	0.009		c_{31}	North	-8.9064×10^{-11}
	γ_{32} -1.1412×10^{-9}	-0.414		c_{32}	East	1.0899×10^{-9}
	γ_{34} -1.1798×10^{-8}	-0.515		c_{34}	Mid-west	1.1268×10^{-8}
Mid-west	α_4 1.3712	11.831	***	a_4	Word of mouth	3.1568×10^{-1}
	β_4 2.1099×10^{-7}	3.836	***	c_{44}	Intra-regional	-1.7944×10^{-7}
	γ_{41} 1.623×10^{-8}	0.772		c_{41}	North	-1.3814×10^{-8}
	γ_{42} 3.1474×10^{-9}	0.521		c_{42}	East	-2.6767×10^{-9}
	γ_{43} -5.7607×10^{-8}	-3.101	***	c_{43}	South	4.8992×10^{-8}

Notes: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

IC design firms to invest in setting up subsidiaries in these four regions for the purpose of business growth or cost advantage savings. The results of positive word-of-mouth coefficient a_i in the four-dimensional Lotka-Volterra models suggest that Chinese employees have become familiar with machine operations as Taiwanese IC design firms set up factories in Chinese regions. Consequently, more and more skilled labor pool together in these regions. Incumbent firms communicate the advantages of low labor costs in Mainland of China to successive firms, which potentially imitate incumbent firms and set up Chinese divisions. Positive a_i in our four-dimensional Lotka-Volterra models represents the good word-of-mouth of the experienced firms, which implies that good word-of-mouth attracts successive firms to continuously invest within the same region, thus, enhancing the growth of Taiwan's IC design industrial clusters in these four Chinese regions.

Table 1 shows that the intra-regional parameters c_{ii} of the four regions are all negative, which describes the self-limitation of each region. Although the degree of significance is different in each region, we can conclude that the saturation within the same region will limit the region's strength for growth. As the investment capital increases and approaches saturation, the growth rate will decrease. The investment amount of Taiwan's IC design companies will crowd out potential investors and prevent them from venturing into the same area. As the continued investment in factories and human resources approaches

saturation, the growth rate of the investment within the same region will decline. This signifies that the developments and growth in North, East, South, and Mid-west China are not limitless. They are bounded by the limitation of each region's resources, such as space, labor, and electricity, which constitute the basic apparatus for developing the IC industry. Furthermore, the increase in labor cost will result in decreased incentives for continuous investment and lead to saturation status.

As for the inter-dependency across various industrial clusters, the positive inter-regional parameters c_{21} and c_{23}, which denote the effect of industrial clusters in North and South China on the clustering growth in East China. It suggests that Taiwanese IC design companies pooling in North and South China promote the clustering of Taiwanese IC design firms into East China. The features and characteristics of industrial clusters vary across different regions in Mainland of China. In North China, industrial clusters center cities include Beijing, Tianjin, Dalian, and Jinan, where a high-quality human resource in the electronics industry is cultivated by the Chinese Academy of Sciences, Peking University, and Tsinghua University. The region focuses on the R&D of high-end products. South China is geographically near Hong Kong and Macau. When Mainland of China began its Economic Reformation Policy in 1979, Shenzhen was established as a special economic district, dominated by foreign investments. The advantages of this area include the quality and cost of human resources, the integrity of the IC manufacturing industry, and the preferable location for entering the vast market. As Taiwan's IC design firms clustered into North and South China, the wages rise substantially; thus, Taiwan's IC design firms increase to invest in East China, where originally there has high price level to provide sales and services to original equipment manufacturers (OEMs) of notebooks, PCs, and mobile phones over there. In Shanghai, Quanta Computer Inc. and Inventec Corporation established factories. Acer, FIC, and ASUS located their factories in Suzhou. In Wujiang, Arima, Compal, and Delta Electronics Incorporations set up their production centers. These electronics firms have developed close relations on the supply-demand chain with the Taiwanese IC design industry. The top ten Chinese cities, by ranking order, to which Taiwanese high-technology industries are willing to invest, are Suzhou, Kunshan, Shanghai, Beijing, Xiamen, Ningbo, Shenzhen, Hangzhou, Zhongshan, and Nanjing according to the investigations of Taiwan Electrical and Electronic Manufacturers' Association. Six of the above ten cities are located within the East China region where the complete supply chain of the electronics and semiconductor industries is located.

The coefficient γ_{43} is significant, which denotes the inter-regional coefficient c_{43} of the IC design industrial clusters in South China on the cluster evolutions into Mid-west China. It suggests that Taiwan's IC design industrial clusters in South China foster the growth of that in Mid-west China to the greatest extent. Because Mid-west China lacks location advantages such as cost reduction, profitability, and public facilities advantages, Mainland of China has implemented balanced development policies since 2005 to develop the economics for Mid-west China. Regarding Mainland of China's 11th Five-Year Plan (2006-2010), the central and municipal government provided many preferential measures such as the income tax exemption, enterprise income tax reduction of "five-year exemption and five-year half payment", venture funds for business start-up and subsidy for the semiconductor wafer production expenses for foreign direct investors who set up factories in Mid-west China. In addition, the municipal government also provided special preferential policies for setting up factories in Mid-west China. Consequently, various governmental policies and creative incentives in Mid-west China strongly attract enterprises that had originally invested in South China to come and set up IC industrial clusters in Mid-west China. International brands including Intel, Infineon, Micron, Applied Material, and Synopsys have invested in this area in recent years. The trend for other IC enterprises to follow

their steps and move to Mid-west China is obvious. The people in Mid-west China are poorer than other regions. Chinese balanced development policies give preferential treatment to foreign investment in Mid-west China to promote the development of industries and improve the income of the people in Mid-west China, to achieve the goal of regional balance.

Possible reasons for the above phenomenon are that the Taiwanese IC design industry has already established a solid foundation in South China. Consequently, the wages in the coastal cities grow as South China become highly developed, causing an increase in operating costs. As a result, successive downstream manufacturers, who are especially sensitive to labor costs, moved their manufacturing factories to Mid-west China, where the labor costs are much lower than in other regions, to expand their production capacity and market. The environment of the Mid-west region itself may not be able to directly draw the Taiwanese IC design industry to form industrial clusters in Mid-west China. These preferential measures attract Taiwanese IC design firms, which have already established subsidiaries in South China, to come and set up more subsidiaries in Mid-west China. In other words, the cluster expansion growth of the Taiwanese IC design industry in Mid-west China depends on the industrial cluster expansion from South China. Our results concurred with the expected consequence of governmental balanced regional development policies.

4.2. **Forecast accuracy of four-dimensional Lotka-Volterra equations.** This investigation selects the test sample to examine the forecast accuracy ranging from the first quarter of 2021 to the first quarter of 2023. Table 2 shows the actual investment amount and predicted investment amount using the proposed four-dimensional Lotka-Volterra equations for Taiwanese IC design firms flowing into North, East, South, and Mid-west China, respectively. The MAPEs of North, East, South and Mid-west China of the four-dimensional Lotka-Volterra equations are 8.4764%, 14.9894% 7.4797% and 12.4559% respectively, and they are all smaller than 20%. According to the criteria of Marin and Witt [28], the prediction ability of our proposed four-dimensional Lotka-Volterra equations is excellent for North and South China but good for East and Mid-west China. It is obvious that four-dimensional Lotka-Volterra equations accurately forecast North, South East and Mid-west China because our proposed four-dimensional Lotka-Volterra equations consider the impact of balanced regional development policies on industrial clustering tendency. Our proposed four-dimensional Lotka-Volterra equations consider the impact of balanced regional development policies, while the Bass model ignores the balanced regional development policies. Thus, our proposed four-dimensional Lotka-Volterra equations perform better in predicting the investment amount from Taiwan to Mainland of China than the Bass model. The forecast accuracy in South China is similar between our four-dimensional Lotka-Volterra equations and Bass model.

Table 2. The MAPE of Lotka-Volterra equations and Bass model in test sample

	Lotka-Volterra	Bass
North China	8.4764%	31.5556%
East China	14.9894%	27.0896%
South China	7.4797%	7.8282%
Mid-west China	12.4559%	23.3607%

Figures 1 to 4 show the actual investment amount, predicted investment amount using the proposed four-dimensional Lotka-Volterra equations and predicted investment amount using the Bass model for Taiwanese IC design firms flowing into North, East, South and

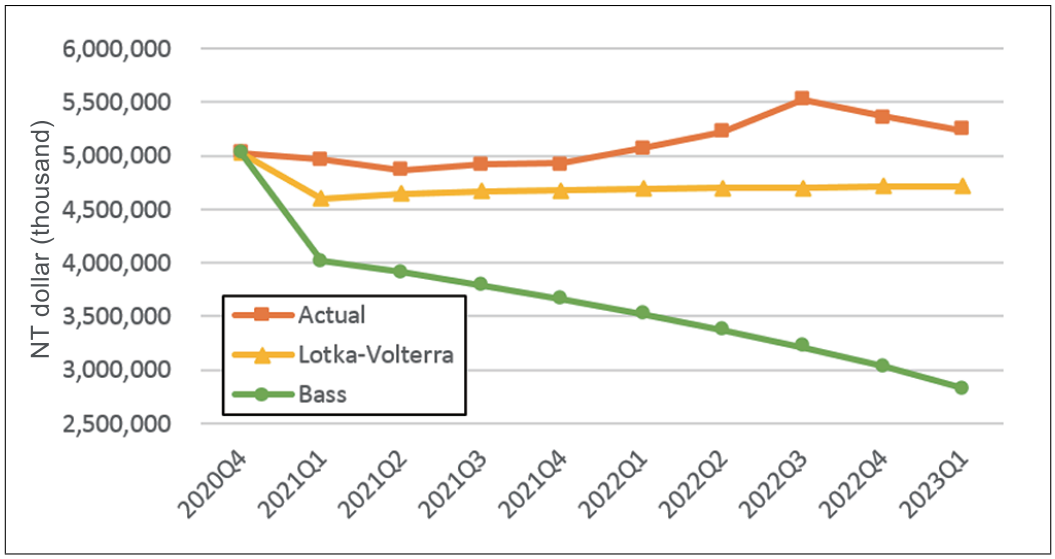

FIGURE 1. A comparison of the actual and the predicted industrial cluster size in North China (unit: thousand NT dollars)

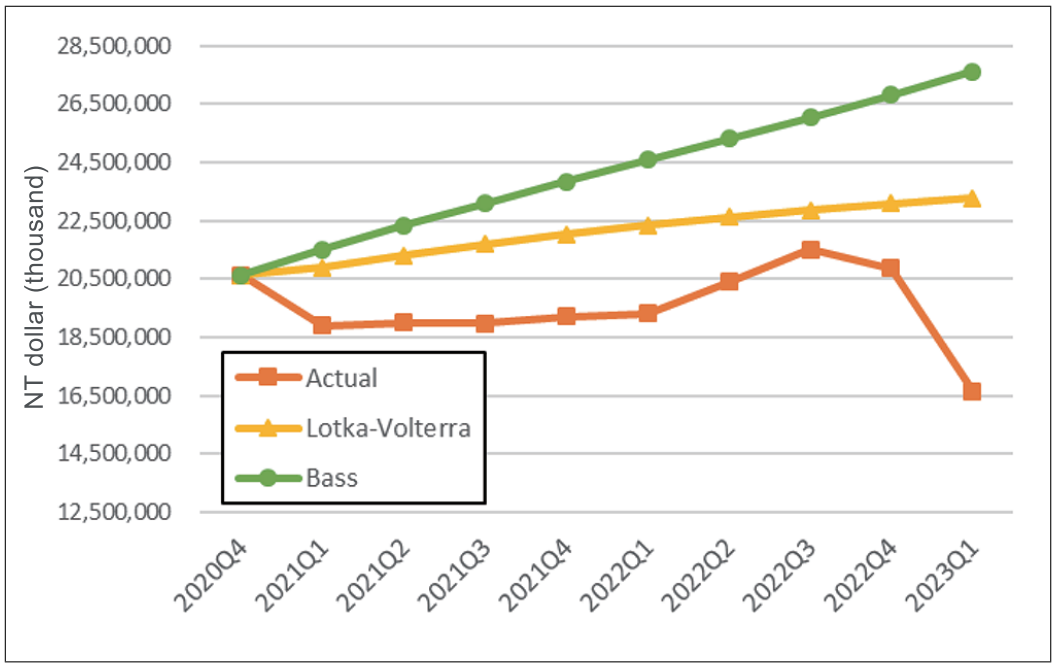

FIGURE 2. A comparison of the actual and the predicted industrial cluster size in East China (unit: thousand NT dollars)

Mid-west China, respectively from the first quarter of 2021 to the first quarter of 2023. Obviously, the actual investment value is close to the investment value predicted by the proposed four-dimensional Lotka-Volterra equations for Taiwanese IC design firms flowing into North and East China. Particularly, Figure 4 shows that the actual value far exceeds the predicted values of the Bass model investment amount for Taiwanese IC design firms flowing into Mid-west China.

5. **Conclusions.** The clustering of Taiwanese IC design firms in various Chinese regions is elucidated. Through four-dimensional Lotka-Volterra equations, this work investigates whether Chinese balanced regional development policies have a substantial influence on

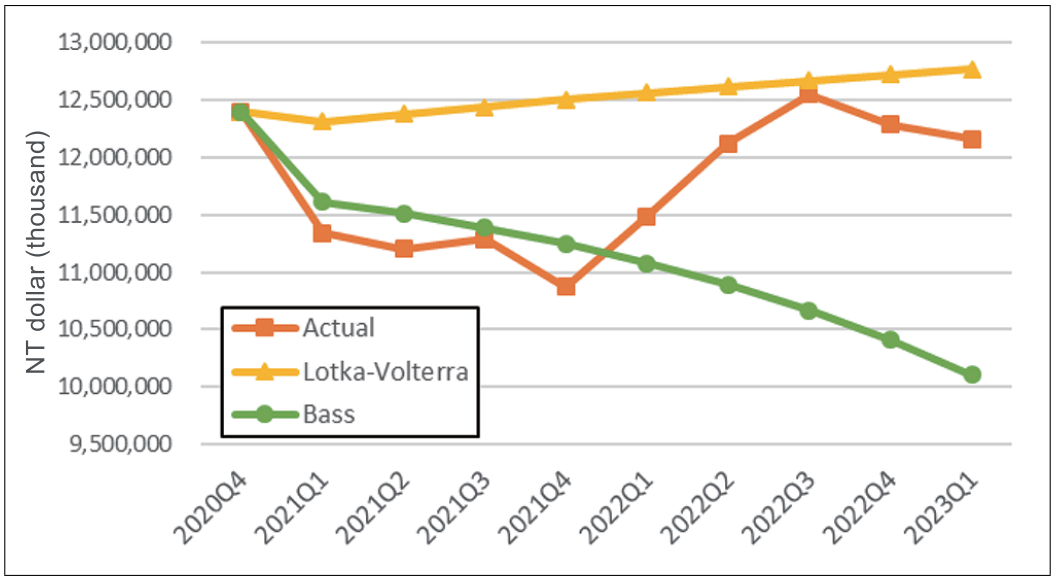

FIGURE 3. A comparison of the actual and the predicted industrial cluster size in South China (unit: thousand NT dollars)

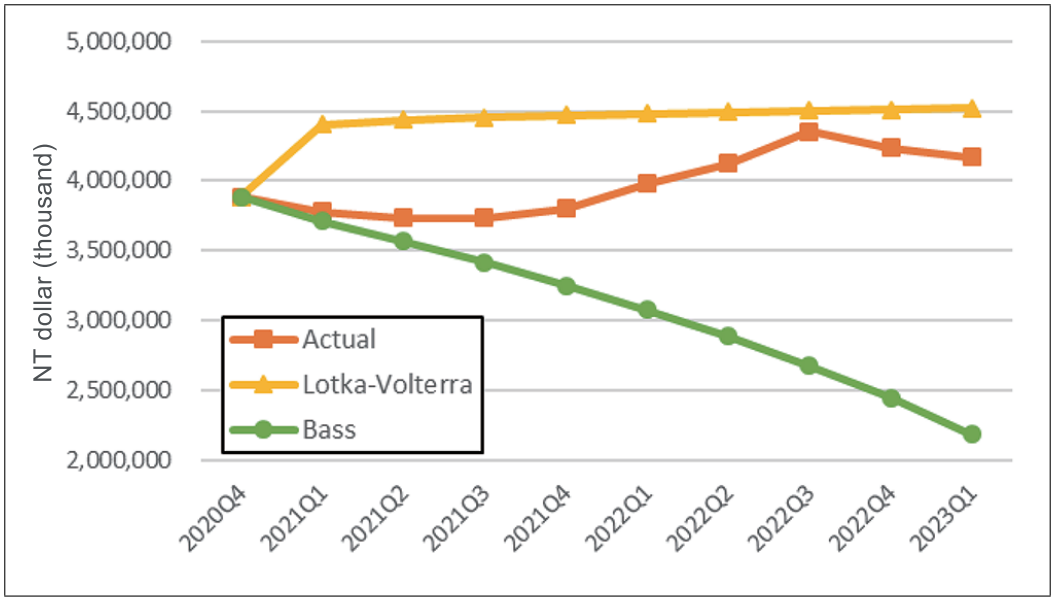

FIGURE 4. A comparison of the actual and the predicted industrial cluster size in Mid-west China (unit: thousand NT dollars)

the location selection of Taiwanese IC design firms when they invest to set up factories in Mainland of China. Our parameter estimation results show that word-of-mouth among incumbent Taiwanese firms is found to stimulate cluster expansion in North, South and Mid-west China. Also, Chinese balanced regional development policies stimulate the industrial clustering growth of Taiwanese IC design firms in Mid-west China. It is possibly caused by the fact that the Taiwanese IC design industry has already established a solid foundation in South China. Labor wages in the coastal cities grow substantially as South China become highly developed, leading to an increase in operating costs. As a result, downstream manufacturers who are especially sensitive to labor costs moved their manufacturing factories to Mid-west China, which increasingly provides tax preferential incentives to attract foreign investment enterprises since 2006. In order to obtain low

wage costs and tax preferential incentives, Taiwan's IC design enterprises previously investing in South China have transferred to invest in the Mid-west China and achieve the purpose of the Chinese balanced regional development policies. Our results suggest that the location selection strategies for Taiwanese IC design industries to invest in Mainland of China is to be close to the market to easily provide customer services. The other strategy is to choose areas with Mainland of China's tax preferential policy to reduce costs. Since East China and South China had once granted Taiwan IC design firms preferential tax credits between 1990 and 2005. Also, East China and South China are geographically close to Taiwan, so Taiwanese IC design firms substantially set up factories in East China and South China. Thus, East China and South China are the largest and second-largest Taiwanese IC design industrial clusters. Conversely, although North China has better research and development talents than other regions, North China is farther away from the customers and lacks tax preference in comparison with East China and South China.

This study further finds that our proposed novel four-dimensional Lotka-Volterra equations accurately predict industrial cluster size in Mainland of China that are formed by IC design firms from Taiwan. The results of forecast accuracy show that our proposed four-dimensional Lotka-Volterra equations can accurately verify the investment trajectory from Taiwanese IC design firms to East, South, North, and Mid-west China. Particularly, our proposed four-dimensional Lotka-Volterra equations outperform the conventional Bass model in predicting Taiwan's industrial cluster size of IC design firms in Mid-west China because our proposed model considers the Chinese balanced regional development policies and corresponds to the practical industrial clustering environments. The contribution of this work is that our proposed four-dimensional Lotka-Volterra equations consider the governmental policies of balanced regional development. Thus, the forecast ability of our proposed four-dimensional Lotka-Volterra equations is better than the conventional Bass model.

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