Hindawi
Mathematical Problems in Engineering
Volume 2023, Article ID 1659050, 10 pages
https://doi.org/10.1155/2023/1659050

Research Article

Game Analysis of Container Ports Co-Competition and Coordinated Development in Guangdong-Hong Kong-Macao Greater Bay Area

Shan Liang[1] **Xuanfei Wang**[2] **and Zhenjie Liao**[3]

[1]*School of Economics, Guangzhou City University of Technology, Guangzhou 510800, China*
[2]*School of Information, Guangdong Intelligent Business Engineering Technology Research Center, Guangdong University of Finance & Economics, Guangzhou 510320, China*
[3]*School of Management, Guangzhou Huashang College, Guangzhou 511300, China*

Correspondence should be addressed to Zhenjie Liao; liaozhenjie_2002@163.com

Received 28 July 2022; Revised 10 December 2022; Accepted 22 December 2022; Published 3 January 2023

Academic Editor: Eduardo Lalla-Ruiz

Copyright © 2023 Shan Liang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The port groups of the Guangdong-Hong Kong-Macao Greater Bay Area faces a new competitive and cooperative game structure concerning global competition, making it is necessary to build a comprehensive port coordination and development mechanism. In this study, we apply the logistics model to conduct parameter estimation and evolution trend analysis on the development of the port group and highlight that the current container throughput of the Guangdong-Hong Kong-Macao Greater Bay Area port group will reach the maximum and the new impetus is needed to push it into the next round of development and evolution. Combined with the theory of ecological population, the Lotka–Volterra model of multiple groups is introduced to study competition and cooperation game, explore their interaction, and provide quantitative support for the formation of different central port groups in the Guangdong-Hong Kong-Macao Greater Bay Area. The study provides references for strengthening the construction of complementary resources and coordinated mechanism within the port group, realizing the differential development between ports in the Guangdong-Hong Kong-Macao Greater Bay Area.

1. Introduction

Bay area economy is a new field in current economic and social development; it leads regional economic development [1–3]. Currently, the Guangdong-Hong Kong-Macao Greater Bay Area (henceforth, Greater Bay Area) construction is steadily progressing. As the core node of the commodity market supply chain in the Greater Bay Area [4], competition between ports is particularly fierce, reflected in both coastline natural resources and market supply. Owing to economic hinterland overlap, this competitive relationship is becoming increasingly prominent in the Greater Bay Area port group's current development process. Because of influences from the social system, capital environment, and other factors, the Greater Bay Area ports have formed a multicenter port group development model with the Hong Kong, Shenzhen, and Guangzhou ports as the center and the surrounding feeder ports choosing to embrace the central port. The competition and cooperation among regional ports are primarily manifested in greater competition between ports of the same level and mutually beneficial symbiosis or predator-prey relations between ports of different levels. The ports' coordinated development has become a major strategic choice for the Greater Bay Area in the new era. Therefore, to better guide development requires analyzing the game behavior of the port groups in the area and quantifying the interaction between the central ports and central ports and branch ports, as well as among branch ports.

Currently, the pace of China's economic structure adjustment is increasing, and the requirements for coordinated port development are increasing [5]. This is manifested in ports changing from simple competition, based on their own development and social resource optimization, to a degree of cooperation, which gives full play to cooperative advantages to achieve the synergy of maximizing benefits [6, 7].

In the literature, Jiang et al. introduced an analysis framework for port connectivity from a global container liner shipping network perspective [8]. Marasco and Romano proposed an integrable nonautonomous Lotka–Volterra model in conducting a quantitative study of the interaction among container ports located in the Le Havre–Hamburg range [9]. Hintjens showed how the port authority can be advantageous for cooperation with adjacent port authorities [10]. Yang et al. employed Landsat images from 1987, 1997, 2007, and 2017 to derive the urban bay area's using the object-oriented support vector machine (O-SVM) classification method; a multiscale spatial analysis method detected the landscape characteristics and types of growth in the urban expansions [11]. Park and Kim conducted an importance-performance analysis (IPA) on the importance of consideration factors before entering the port hinterland and satisfaction of consideration factors after moving to Busan and Gwangyang ports [12]. Twrdy and Zanne addressed the problem of sustainability of ports logistics and presented current conditions in the Port of Koper, the Mediterranean port located in the North Adriatic [13]. Fan et al. combined the dual competition of market demand competition and shoreline resources faced by China's ports and established a game model to analyze port competition and cooperation in the Yellow Sea [14]. Zhao et al. conducted quantitative research on the port system's competition and cooperation relationships against the background of constructing China's 21st century Maritime Silk Road [15].

Through systematic research and analysis, Kuang et al. highlighted that port city separation constitutes a breakthrough in China's port supply side reform [16]. Guo and Yang studied the integration of ports in Northeast China from the perspective of maximizing the internal transportation social welfare of the outward transportation system [17]. Lai et al. discussed the revenue of the port competition and cooperation game and the coordination mechanism of the port supply chain [18]. Yu and Xu researched the income status of adjacent inland ports under different types of competition strategies based on the Hotelling model [19].

Presently, many provinces in China have established provincial port groups through provincial government investment or have relied on existing provincial state-owned enterprises. As the core platform for ports' coordinated development, this path has distinct top-down authority and easily becomes large scale in a short time. However, the coordinated development of ports in the Greater Bay Area goes beyond the scope of provinces and systems and involves stakeholders at different levels. The construction of a port coordinated development mechanism is more difficult. Most existing studies on the Greater Bay Area ports are qualitative analyses with a few quantitative studies based on the results of the relevant Pearl River Delta ports.

For example, Luo et al. took the terminal price competition and scale expansion between Hong Kong and Shenzhen ports as the research object and established a two-stage game model to launch [20]. Wang et al. outlined the importance of the Regional Port Alliance based on an analysis of the game model established by the Pearl River Delta ports [21]. Cheng et al. took the Hong Kong and Shenzhen ports as the research objects to provide a quantitative discussion on port trade facilitation [22]. Yu and Shan established a quantitative model to study the competition and cooperation game relationship between ports from the perspectives of local governments and container terminals [23]. Xia established a container port alliance model based on a game theory and analyzed the income distribution and functional solution of a cooperative game [24]. Wang et al. compared the competition between the Shenzhen port and the Guangzhou and Hong Kong ports using the factor analysis method [25]. In sum, quantitative research on the game analysis of ports' coordinated development in the Greater Bay Area is limited, and a development mechanism for reference and promotion is absent. Considering the important significance of ports in the construction of the Greater Bay Area, we explore the port interaction mechanism of the Greater Bay Area from the perspective of the competition and cooperation game to provide reference for the coordinated development of area ports.

2. Model Construction

2.1. Evolution Analysis of the Port Group in the Guangdong-Hong Kong-Macao Greater Bay Area. Biological population development and evolution in a certain area show that survival is inseparable from the ecological environment [26]. The population will multiply and die as per natural law, and its strength will dynamically change [27]. Simultaneously, the population evolves through adaptation and changing the environment [28]. Different populations in the same area may portray either predator-prey relations, competitive relations, or mutually beneficial symbiotic relations because of resource competition [29]. Similarly, in the case of ports, dynamic port economic developments relate closely to port location and comprehensive management changes. Owing to port economic structure and comprehensive environment changes, a port undergoes dynamic changes [30]. Port growth and evolution follow certain rules; that is, the speed is slow in the early and late stages, and it increases rapidly in the middle stages. The overall evolutionary process presents an S-shaped curve, which is consistent with a biological population's growth and evolutionary law. Therefore, the logistics model, which was first used to study the evolutionary law of biological populations [31], is introduced into studying port evolution here. The formula is as follows:

$$\frac{dP(t)}{dt} = \alpha P\left(1 - \frac{P}{H}\right), \tag{1}$$

where $P(t)$ denotes the port group scale of the Greater Bay Area at time t, α denotes the throughput growth rate of the port group, and H denotes the maximum value of the port scale. By solving the differential equation with the above-mentioned formula, we obtain the following:

$$P(t) = \frac{H}{1 + e^{\varepsilon - \alpha t}} \ (H > 0, \alpha > 0), \quad (2)$$

where $\varepsilon = \text{Ln}[H/P(0) - 1]$, $P(0)$ denotes the port scale at the initial time, and $(\varepsilon/\alpha, H/2)$ denotes the turning point of port evolution trend. Since container throughput has become an important indicator of the port group's scale, we use the Greater Bay Area's container throughput data to represent the port group scale (Table 1) and estimate the parameters of the group's container throughput data from 1999 to 2018 in combination with the logistics model. The development and evolution trend of the port group is fitted.

According to the parameter estimation results (Table 2) and evolution trend (Figure 1) of the Greater Bay Area port group logistics model, the inflection point of the bay's evolution appeared in 2005 $(1999 + 1.2377/0.2315 = 2005)$. Before that, the port group's container scale increased rapidly, and the growth rate peaked in 2005. Since then, the growth rate of the port group's container scale has shown the characteristics of instability. The aforementioned phenomenon is mainly affected by changes in China's port control mode. After entering the 21st century, China's port control mode has gradually changed from the central government to the coexistence of local government and the market. After the decentralization of port management power, the enthusiasm of local governments to build ports was mobilized. Relying on its geographical advantages, Shenzhen port has introduced Hong Kong port enterprises, which has continuously participated in the operation and management of Shenzhen port through shares and therefore greatly promoted the growth of port scale [32, 33]. After 2017, the Greater Bay Area port group's container throughput will reach its limit. The main reason is that the Chinese government has once again issued port management policies to encourage private capital to participate in port reform. The continuous construction of and vicious competition among ports are serious issues, and ports' insufficient division, cooperation, and differentiated development lead to excess supply. Therefore, new impetus is needed to promote the Greater Bay Area port group's entry into a new development and evolutionary process.

Our analysis results are in good agreement with the current scale development of port clusters in the Greater Bay Area. In recent years, the Greater Bay Area port group confronted a new competition and cooperation game pattern regarding participation in the global competition. With the emergence of the sluggish global shipping market in the postcrisis period, the problems of the Greater Bay Area port group are gradually being exposed, which will affect the region's long-term development. Presently, the pace of economic structure adjustment in the Greater Bay Area is accelerating, and the coordinated development requirements of port groups are becoming increasingly higher. This requires strengthening constructing the complementary and coordinated development mechanism of port groups in the Greater Bay Area to realize differentiated development.

Table 1: Container throughput of the Guangdong-Hong Kong-Macao Greater Bay Area from 1999 to 2018.

Years	Throughputs (10000TEU)	Years	Throughputs (10000TEU)
1999	2116	2009	5663
2000	2558	2010	6597
2001	2715	2011	6899
2002	3232	2012	6896
2003	3763	2013	6992
2004	4403	2014	7352
2005	4846	2015	7325
2006	5488	2016	7473
2007	6032	2017	8035
2008	6304	2018	8117

Table 2: Estimation results of port group in Guangdong-Hong Kong-Macao Greater Bay Area.

	Coef	Std. err.	t	$P > \lvert t \rvert$	95% conf.	Intervals
/betal1	8030.5450	214.22	37.49	0.000	7578.580	8482.511
/betal2	1.2378	0.0924	13.39	0.000	1.0427	1.4328
/betal3	0.2315	0.0201	11.51	0.000	0.1891	0.2739

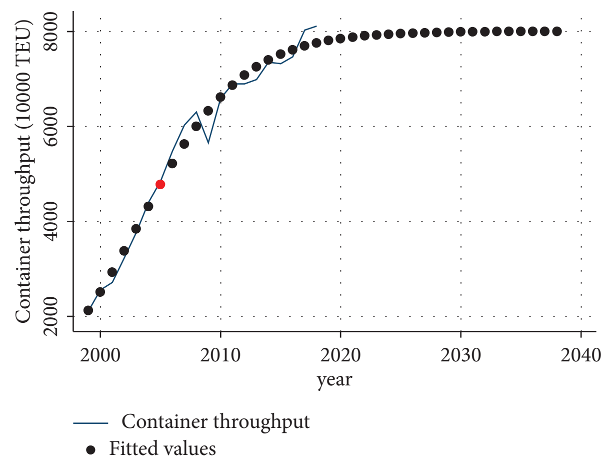

Figure 1: Fitting of evolution trend of the port group in the Guangdong-Hong Kong-Macao Greater Bay Area.

2.2. Model Establishment. The Lotka–Volterra model was originally proposed by American ecologist Lotka and Italian mathematician Volterra [34, 35]. The model is used to study the interaction of different populations in the same environment. Within the same spatial and temporal range, different populations compete for limited resources and establish predator-prey relations and mutual-symbiosis relations. As an important theoretical method to study the evolution and development of ecological populations, the Lotka–Volterra model can intuitively reflect the relationship between different populations. It is widely used in logistics industry development [36, 37], industrial ecology [38, 39], and network innovation [40]. This model is currently often applied in the port field, primarily to explore the interaction relationship between two or three ports [41, 42]. However, there are often no less than three ports in the same region. Related studies on multiple ports in the same region are mainly discussed from the economics perspective, such as the research on port city development using the PSM-DID method [43], the comparative study on operation efficiency of port container terminals based on a DEA model [44], and the research on port throughput prediction based on a dynamic penalized support vector regression model [45]. The interaction relationship, however, between multiple ports is rarely quantified. In view of its wide application in the academic field, this study expands and introduces the Lotka–Volterra model into our research to examine the interaction relationship between ports, using the competition and cooperation game of the Greater Bay Area port groups as an example. The interaction between ports can be represented by the following mathematical symbols:

(1) *Promoting Effect*. Port i is positively correlated with the change of port j scale, which is recorded as $i(+) \longrightarrow j$

(2) *Hindrance*. Port i is negatively correlated with the change of port j scale, which is recorded as $i(-) \longrightarrow j$

Thus, three different port relationship modes are formed:

(i) *Mutually Beneficial Symbiosis between Ports*. Namely, $i(+) \longrightarrow j$ and $j(+) \longrightarrow i$

(ii) *Competition between Ports*. Namely, $i(-) \longrightarrow j$, and $j(-) \longrightarrow i$

(iii) *Predator-Prey Relationship between Ports*. Namely, $i(-) \longrightarrow j$ and $j(+) \longrightarrow i$

Considering the actual port development in the Greater Bay Area and the principle of port coordination from easy to difficult, we apply the multigroup Lotka–Volterra model to our research on the competition and cooperation game of its nine ports in mainland China and establish the multigroup Lotka–Volterra model as shown in the following formula:

$$\begin{cases} \dfrac{dP_1(t)}{dt} = \alpha_1 P_1\left(1 + \beta_{12}\dfrac{P_2}{H_2} + \beta_{13}\dfrac{P_3}{H_3} + \cdots + \beta_{19}\dfrac{P_9}{H_9}\right), \\ \dfrac{dP_2(t)}{dt} = \alpha_2 P_2\left(1 + \beta_{21}\dfrac{P_1}{H_1} + \beta_{23}\dfrac{P_3}{H_3} + \cdots + \beta_{29}\dfrac{P_9}{H_9}\right), \\ \vdots \\ \dfrac{dP_9(t)}{dt} = \alpha_9 P_9\left(1 + \beta_{91}\dfrac{P_1}{H_1} + \beta_{92}\dfrac{P_2}{H_2} + \cdots + \beta_{98}\dfrac{P_8}{H_8}\right). \end{cases} \tag{3}$$

Among them, $P_i(t)\,(i = 1, 2, \ldots, 9)$ are the container throughputs of the nine Greater Bay Area ports at t time, $\alpha_i\,(i = 1, 2, \ldots, 9)$ is the growth rate of port i, $\beta_{ij}\,(i, j = 1, 2, \ldots, 9)$ is the influence coefficient of port j on port i, and $\mathrm{H_i}\,(i = 1, 2, \ldots, 9)$ is the maximum handling capacity of port i. We convert the abovementioned model into the following formula:

$$\begin{cases} \dfrac{dP_1(t)}{dt} = \lambda_{11}P_1 + \lambda_{12}P_1P_2 + \lambda_{13}P_1P_3 + \cdots + \lambda_{19}P_1P_{9,} \\ \dfrac{dP_2(t)}{dt} = \lambda_{22}P_2 + \lambda_{21}P_1P_2 + \lambda_{23}P_2P_3 + \cdots + \lambda_{29}P_2P_{9,} \\ \vdots \\ \dfrac{dP_9(t)}{dt} = \lambda_{99}P_9 + \lambda_{91}P_1P_9 + \lambda_{92}P_2P_9 + \cdots + \lambda_{98}P_8P_{9.} \end{cases} \tag{4}$$

Based on the grey derivative and even logarithm mapping relationship, the following formula is obtained:

$$\begin{cases} P_1(t+1) - P_1(t) = \lambda_{11}\dfrac{P_1(t+1) + P_1(t)}{2} + \lambda_{12}\left[\dfrac{P_1(t+1) + P_1(t)}{2}\right]\left[\dfrac{P_2(t+1) + P_2(t)}{2}\right] + \cdots + \lambda_{19}\left[\dfrac{P_1(t+1) + P_1(t)}{2}\right]\left[\dfrac{P_9(t+1) + P_9(t)}{2}\right], \\ P_2(t+1) - P_2(t) = \lambda_{22}\dfrac{P_2(t+1) + P_2(t)}{2} + \lambda_{21}\left[\dfrac{P_1(t+1) + P_1(t)}{2}\right]\left[\dfrac{P_2(t+1) + P_2(t)}{2}\right] + \cdots + \lambda_{29}\left[\dfrac{P_2(t+1) + P_2(t)}{2}\right]\left[\dfrac{P_9(t+1) + P_9(t)}{2}\right], \\ \vdots \\ P_9(t+1) - P_9(t) = \lambda_{99}\dfrac{P_9(t+1) + P_9(t)}{2} + \lambda_{91}\left[\dfrac{P_1(t+1) + P_1(t)}{2}\right]\left[\dfrac{P_9(t+1) + P_9(t)}{2}\right] + \cdots + \lambda_{98}\left[\dfrac{P_8(t+1) + P_8(t)}{2}\right]\left[\dfrac{P_9(t+1) + P_9(t)}{2}\right]. \end{cases} \tag{5}$$

We substitute $t = 1, 2, 3, \cdots, n$ time data into the following formula and obtain the matrix equation $X_{in} = \kappa_i \hat{\lambda}_i$ $(i = 1, 2, \ldots, 9)$; taking Guangzhou port as an example, its matrix equation is $X_{2n} = \kappa_2 \hat{\lambda}_2$, where

$$\kappa_2 = \begin{bmatrix} \frac{P_2(1)+P_2(2)}{2} & \left[\frac{P_1(1)+P_1(2)}{2}\right] & \cdots & \left[\frac{P_2(1)+P_2(2)}{2}\right]\left[\frac{P_9(1)+P_9(2)}{2}\right] \\ \frac{P_2(2)+P_2(3)}{2} & \left[\frac{P_1(2)+P_1(3)}{2}\right]\left[\frac{P_2(2)+P_2(3)}{2}\right] & \cdots & \left[\frac{P_2(2)+P_2(3)}{2}\right]\left[\frac{P_9(2)+P_9(3)}{2}\right] \\ \vdots & \vdots & & \vdots \\ \frac{P_2(n-1)+P_2(n)}{2} & \left[\frac{P_1(n-1)+P_1(n)}{2}\right]\left[\frac{P_2(n-1)+P_2(n)}{2}\right] & \cdots & \left[\frac{P_2(n-1)+P_2(n)}{2}\right]\left[\frac{P_9(n-1)+P_9(n)}{2}\right] \end{bmatrix}. \quad (6)$$

$X_{2n} = [P_2(2) - P_2(1), P_2(3) - P_2(2), \cdots, P_2(n) - P_2(n-1)]^T$, $\hat{\lambda}_2 = [\lambda_{22}, \lambda_{21}, \lambda_{23}, \cdots, \lambda_{29}]^T$. Using the least square rule, there are

$$\hat{\lambda}_2 = \left((\kappa_2)^T \kappa_2\right)^{-1} (\kappa_2)^T X_{2n}. \quad (7)$$

3. Empirical Research

3.1. Quantification of Port Parameters. In the Greater Bay Area, according to the degree of administrative subordination, most of the leading ports in various cities belong to local governments; other ports in the same city are also under their control. Therefore, this paper regards the ports in the Greater Bay Area as an area of interest to analyze the interaction between ports. These independent individuals represent the whole of the ports in the Greater Bay Area. Based on the division of administrative regions and the interests of local governments in China, this analysis basically represents the interrelationship between various cities and ports within the Greater Bay Area. Therefore, we substitute the container throughput data of the nine ports from 1999 to 2018 and repeat this step to obtain the matrix equation parameters $\hat{\lambda}_i = (i = 1, 2, \ldots, 9)$, as shown in Table 3.

3.2. Port Competition and Cooperation Analysis. According to the conversion relationship between parameter $\hat{\lambda}_{ij} = (i, j = 1, 2, \ldots, 9)$ and the influence coefficient β_{ij} between ports, the positive and negative parameters $\hat{\lambda}_{ij}$ and β_{ij} are consistent and can be used to analyze the interaction relationship of the nine ports (Table 4):

(1) For Shenzhen port and Guangzhou port, $\hat{\lambda}_{12} < 0$, indicating that Guangzhou port negatively affects Shenzhen port, and $\hat{\lambda}_{21} > 0$, indicating that Shenzhen port positively affects Guangzhou port. That is, the two ports have a predator-prey relationship, where Shenzhen port is the predator and Guangzhou port is the predator. (The analysis here is on the interaction between the nine ports in the Guangdong-Hong Kong-Macao Greater Bay Area, which may be different from the analysis of the interaction between the central ports in the Greater Bay Area alone, because Guangzhou port and Shenzhen port have formed two different management and control modes. During the analysis within the Greater Bay Area, this makes Guangzhou port's advantage in integrating other neighboring ports by administrative means more prominent, which demonstrates that the same population affects the results in different ecological environments and further verifies the rationality of introducing the Lotka–Volterra model based on the ecological population theory discussed in Section 2.2.) Regarding its relationship with Dongguan port, Shenzhen port is the predator and Dongguan port is the predator. With Foshan port, Shenzhen port is the predator and Foshan port is the prey. With Huizhou port, Shenzhen port is the predator and Huizhou Port is the predator. With Zhaoqing port, Shenzhen port is the predator and Zhaoqing port is the predator. With Zhongshan port, Shenzhen port is the predator and Zhongshan port is the predator. In contrast, Shenzhen port has a mutually beneficial symbiotic relationship with Jiangmen port and a competitive relationship with Zhuhai port.

(2) For Guangzhou port and Dongguan port, $\hat{\lambda}_{23} > 0$, indicating that Dongguan port positively affects Guangzhou port, and $\hat{\lambda}_{32} < 0$, indicating that Guangzhou port negatively affects Dongguan port. That is, the two ports have a predator-prey relationship, where Guangzhou port is the predator and Dongguan port is the prey. As for its relationship with Foshan port, Guangzhou port is the predator and Foshan port is the predator. With Huizhou port, Guangzhou port is the predator and Huizhou port is predator. With Zhongshan port, Guangzhou port is the predator and

Table 3: Ports parameter value of the matrix equation.

	Shenzhen ($j=1$)	Guangzhou ($j=2$)	Dongguan ($j=3$)	Foshan ($j=4$)	Huizhou ($j=5$)	Jiangmen ($j=6$)	Zhaoqing ($j=7$)	Zhongshan ($j=8$)	Zhuhai ($j=9$)
Shenzhen ($i=1$)		−0.0016	0.00647	0.03102	0.00415	0.0084	0.04896	−0.0556	−0.0293
Guangzhou ($i=2$)	0.00038		0.00006	0.00098	−0.0024	−0.0081	−0.003	0.01417	0.00016
Dongguan ($i=3$)	−0.01114	−0.0005		0.00236	0.02789	0.02378	0.05435	0.07361	−0.0043
Foshan ($i=4$)	−0.0011	−0.0008	0.00087		−0.0046	−0.0157	0.01174	0.02807	0.00592
Huizhou ($i=5$)	−0.0168	0.01074	−0.0133	−0.0403		0.0114	−0.1073	0.34306	0.00332
Jiangmen ($i=6$)	0.00018	−0.0017	0.0022	0.01332	−0.0056		0.02183	0.00099	−0.0086
Zhaoqing ($i=7$)	−0.0009	−0.0018	0.00181	0.00781	0.01191	−0.0195		0.01245	0.0573
Zhongshan ($i=8$)	0.00061	−0.0008	0.00156	0.0082	−0.0054	−0.011	0.01472		−0.0038
Zhuhai ($i=9$)	−0.0021	−0.0002	0.00193	0.00605	−0.0071	−0.0434	0.01445	0.0997	

Table 4: Ports co-competition analysis.

	Shenzhen	Guangzhou	Dongguan	Foshan	Huizhou	Jiangmen	Zhaoqing	Zhongshan	Zhuhai
Shenzhen		Predator-prey	Predator-prey	Predator-prey	Predator-prey	Mutually beneficial symbiosis	Predator-prey	Prey-predator	Competitive relationship
Guangzhou			Predator-prey	Predator-prey	Prey-predator	Competitive relations’	Competitive relationship	Predator-prey	Predator-prey
Dongguan				Mutually beneficial symbiosis	Predator-prey	Mutually beneficial symbiosis	Mutually beneficial symbiosis	Mutually beneficial symbiosis	Prey-predator
Foshan					Competitive relations’	Prey-predator	Mutually beneficial symbiosis	Mutually beneficial symbiosis	Mutually beneficial symbiosis
Huizhou						Predator-prey	Prey-predator	Predator-prey	Predator-prey
Jiangmen							Predator-prey	Predator-prey	Competitive relationship
Zhaoqing								Mutually beneficial symbiosis	Mutually beneficial symbiosis
Zhongshan									Prey-predator

Zhongshan port is the predator. With Zhuhai port, Guangzhou port is the predator and Zhuhai port is the predator. In contrast, Guangzhou has a competitive relationship with Jiangmen port and Zhaoqing port.

(3) For Dongguan port and Foshan port, $\hat{\lambda}_{34} > 0$, indicating that Foshan port has a positive effect on Dongguan port, and $\hat{\lambda}_{43} > 0$, indicating that Dongguan port has a positive effect on Foshan port. That is, the two have a mutually beneficial and symbiotic relationship. Similarly, it has a mutually beneficial symbiotic relationship with Jiangmen port, Zhaoqing port, and Zhongshan port, predator-prey relationship with Huizhou Port, Dongguan port, Huizhou port, Zhuhai port, predator relationship with Zhuhai port, and predator relationship with Dongguan port.

(4) For Foshan port and Huizhou port, $\hat{\lambda}_{45} < 0$, indicating that Huizhou port negatively affects Foshan port, and $\hat{\lambda}_{65} < 0$, indicating that Foshan port negatively effects Huizhou port. That is, the two have a competitive relationship. It has a predator-prey relationship with Jiangmen port. Between Foshan port and Jiangmen port, both are predators. It has a mutually beneficial symbiotic relationship with Zhaoqing, Zhongshan, and Zhuhai ports.

(5) For Huizhou port and Jiangmen port, $\hat{\lambda}_{56} > 0$, indicating that Jiangmen port has a positive effect on

Huizhou port, and $\hat{\lambda}_{65} < 0$, indicating that Huizhou port negatively affects Jiangmen port. That is, the two have a predator-prey relationship, where Huizhou port is the predator and Jiangmen port is the predator. With Zhaoqing port, Huizhou port is the predator and Zhaoqing port is the predator. With Zhongshan port and Zhuhai port, Huizhou port is the predator and Zhongshan port and Zhuhai port are the predators.

(6) For Jiangmen port and Zhaoqing port, $\hat{\lambda}_{67} > 0$, indicating that Zhaoqing port has a positive effect on Jiangmen port, and $\hat{\lambda}_{76} < 0$, indicating that Jiangmen port negatively affects Zhaoqing port. That is, the two have a predator-prey relationship, where Jiangmen port is the predator and Zhaoqing port is the predator. In the relationship between Zhongshan port and Jiangmen port, both are predators. In contrast, Jiangmen has a competitive relationship with Zhuhai port.

(7) For Zhaoqing port and Zhongshan port, $\hat{\lambda}_{78} > 0$, indicating that Zhongshan port acts positively on Zhaoqing port, and $\hat{\lambda}_{87} > 0$, indicating that Zhaoqing port positively affects Zhongshan port. That is, the two have a mutually beneficial and symbiotic relationship. Similarly, it also has a mutually beneficial symbiotic relationship with Zhuhai port.

(8) For Zhongshan port and Zhuhai port, $\hat{\lambda}_{89} < 0$, indicating that Zhuhai port negatively affects Zhongshan port, and $\hat{\lambda}_{98} > 0$, indicating that the two have a predator-prey relationship, where Zhongshan port is the predator and Zhuhai port is the predator.

3.3. Coordinated Development of Ports in the Greater Bay Area. According to the abovementioned analysis, Guangzhou, Dongguan, Foshan, Zhongshan, and Zhuhai ports play the role of predator and prey, wherein Guangzhou port is the predator and Dongguan, Foshan, Zhongshan, and Zhuhai ports are also predators. In contrast, Dongguan port and Foshan port, Dongguan port and Zhongshan port, Foshan port and Zhongshan port, and Foshan port and Zhuhai port have formed mutually beneficial symbiotic relationships. Similarly, Shenzhen, Huizhou, and Zhaoqing ports play the role of predator and prey, wherein Shenzhen port is a predator and Huizhou Port and Zhaoqing port are also predators. Shenzhen port and Jiangmen port have formed a mutually beneficial symbiotic relationship. Huizhou, Jiangmen, and Zhaoqing ports also have predator-prey relationship, as do Zhongshan port and Shenzhen port, wherein both are predators. Zhuhai port and Shenzhen port have a competitive relationship, while Huizhou port and Guangzhou port have a predator-prey relationship, wherein both are predators. For Jiangmen, Zhaoqing, and Guangzhou ports, Jiangmen port and Zhuhai port and Huizhou Port and Foshan port have competitive relationships, respectively. Therefore, a port group centered on Guangzhou port (including Guangzhou, Dongguan, Foshan, Zhongshan, and Zhuhai ports) and another centered on Shenzhen port (including Shenzhen, Huizhou, Jiangmen, and Zhaoqing ports) have been formed. Their coordinated development can be divided into coordinated development within the port group, coordinated development between central ports, and coordinated development of the two port groups. The abovementioned analysis is consistent with the current development status of the port group in the Greater Bay Area, because the port group in the Guangdong Province in the area differs from other regions in China. Against the background of the country's efforts to promote port integration, two different types of control modes have been formed, namely, Shenzhen port on the east bank of the Pearl River as a center and Guangzhou port on the south bank of the Pearl River as a center. For example, Shenzhen port and Huizhou port have established a combined port and Guangzhou port has cooperated with Zhongshan port and Zhuhai port, all of which were verified by our analysis.

Combined with the data quantification, history of development, and current situation of the Greater Bay Area ports, coordinated development within the port groups is mainly reflected between a central port and a branch port. For the internal coordination of the port group centered on Guangzhou port, it is necessary to break through the boundary of the administrative management system; overcome local protectionism and administrative constraints; integrate the branch port into the new port group by means of allocation or paid transfer; ensure that the funds invested in the port by the local government are reasonably compensated; strengthen the dislocated division of labor between the branch ports; and find a complex balance of interests. Through policy formulation, the layout of port spatial structure in the form of division of labor and cooperation should be consciously guided. The internal coordination of the port group centered on Shenzhen port must formulate the best operating combination according to its needs so as to approach the market fully, mobilize market enthusiasm to the greatest extent, expand the water transfer mode and the construction of combined ports, and overflow bulk cargo to a cooperative port in the Greater Bay Area.

The coordination between the central ports is mainly reflected in Guangzhou and Shenzhen ports' land and sea hinterlands. Land-based hinterland coordination should dislocate from the collection and distribution system, the destination of goods, and the types of goods. The sea-based hinterland coordination should appropriately adjust the highly competitive routes and cooperate to develop potential advantageous routes based on the degree of urban external contact and development characteristics. The synergy between the two port groups is mainly manifested in the dual progress of government and market leadership. In the port group centered on Guangzhou port, the government department is subject to coordinated development and can actively play a macrocontrol role; however, a risk may exist in terms of coordinated development failure because of ignoring market law. The port group centered on Shenzhen port adheres to a market orientation and forms a staggered community of interests through holdings, joint ventures, and equity replacements; however, this model can easily lead to the polarization of port development. Therefore, it is necessary for government- and market-led approaches to complement each other and their advantages to better promote the coordinated development of ports in the Greater Bay Area.

4. Conclusion

The collaborative development of ports in the Guangdong-Hong Kong-Macao Greater Bay Area is an operation form established for ports of different levels based on common goals to cope with uncertain environment in the new era. It has the characteristics of dynamic, multiple levels, and complexity and can produce optimization effect, complementary effect, and integration effect synergistically. Therefore, it has become an effective way to promote the current supply-side reform of ports.

Based on the game perspective of the coordinated development of ports in the Guangdong-Hong Kong-Macao Greater Bay Area, this paper, first, introduces the logistics model to estimate parameters and analyze the evolution trend of the port cluster in the Guangdong-Hong Kong-Macao Greater Bay Area on the basis of analyzing the consistency between the evolutionary development of regional ports and the growth and evolution law of biological populations. It is pointed out that the container throughput scale of the port cluster in the Guangdong-Hong Kong-Macao Greater Bay Area will reach the limit. Therefore, new impetus is needed to promote the port cluster to enter the next round of development and evolution. Second, combined with the ecological population theory, this study innovatively introduced the expanded multipopulation Lotka–Volterra model into the analysis of the competition and cooperation game of mainland ports in the Guangdong-Hong Kong-Macao Greater Bay Area to explore the interaction between the ports. The research object is different from the existing academic achievements in that there are several central ports in the Guangdong-Hong Kong-Macao Greater Bay Area port cluster that belong to different management and control modes and the central ports have a higher discourse power in the development process and will form different types of port control modes in the future development, while the regional branch ports are limited by their own scale and regional barriers. We choose to cooperate with the central port according to the needs and then form different port cooperation alliances. The study provides a reference for strengthening the complementarity of resource advantages and the construction of collaborative mechanism within the port cluster of the Guangdong-Hong Kong-Macao Greater Bay Area and achieving differentiated development of ports. Third, on the basis of this quantitative analysis, this paper proposes that the ports in the Guangdong-Hong Kong-Macao Greater Bay Area should not only curb competition but also emphasize the stable and orderly cooperation mechanism construction among the ports. Scientific and reasonable top-level design and overall planning are the keys to the coordinated development of the ports in the Guangdong-Hong Kong-Macao Greater Bay Area. The government should formulate supportive policies according to local conditions and properly handle the relationship between the ports. Strengthen the institutional constraint mechanism of port cluster, promote the construction of trust mechanism and benefit distribution mechanism, avoid the moral hazard brought by opportunism, speed up the construction of regional comprehensive transportation hub centered on Guangzhou Port, explore the leading port model centered on Shenzhen Port, and guide the branch ports to actively embrace the central port. The Guangdong-Hong Kong-Macao Greater Bay Area port cluster will be formed into a port coordinated development mechanism with reasonable functional zoning and mutual benefit.

Finally, the game analysis content of port co-competition and coordinated development in the Guangdong-Hong Kong-Macao Greater Bay Area in this paper, which studies and quantifies the interaction between ports, has important guiding significance for the current coordinated development of ports in the Guangdong-Hong Kong-Macao Greater Bay Area. Meanwhile, in order to more accurately grasp the port development dynamics and strive for improvement, factors such as local economic development and port investment should be considered in the study of port competition and cooperation game in the future. In addition, during the double cycle of new development period, the research on the network competition mechanism of the central port cluster in the Guangdong-Hong Kong-Macao Greater Bay Area under different types of management and control modes will also be the next research direction.

Data Availability

The source of the data displayed in the figure is the website of the National Bureau of Statistics and the website of Statistical Information of the Guangdong Province. Data are available at https://stats.gd.gov.cn/, and these data are available free of charge.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

Shan Liang conceptualized the study and performed data curation; Xuanfei Wang performed formal analysis; Xuanfei Wang and Zhenjie Liao wrote the original draft; Shan Liang provided the software; Xuanfei Wang, Shan Liang, and Zhenjie Liao wrote, reviewed, and edited the study. All authors have read and agreed to the published version of the manuscript.

Acknowledgments

This study was financed by a grant from the Guangzhou Huashang College (2022HSKT02); a grant from the Guangzhou Huashang College (2021HSXK10); the Philosophy and Social Sciences of Guangdong Province in the 13th

Five-Year Period (GD20XGL06); the Philosophy and Social Science Grant of Guangzhou in the 14th Five-Year Period (2021GZGJ73); the Educational Science Grant of Guangdong in the 13th Five-Year Period (2019GXJK084); Guangzhou Science Plan Project (202201011273); and the key programme of Low-carbon Economy and Carbon Finance Research Center of Guangzhou City University of Technology (XK-180005).

References

[1] J. Yang, “Economic synergistic development of Guangdong-Hong Kong-Macao greater bay area urban agglomeration: based on composite system,” *Computational Intelligence and Neuroscience*, vol. 2022, Article ID 7677188, 10 pages, 2022.

[2] Y. G. Ren, W. D. Chen, and X. L. Chen, “Application of the BP neural network model in the coordinated development of tourism economic networks in the Guangdong-Hong Kong-Macao greater bay area,” *Computational Intelligence and Neuroscience*, vol. 2022, Article ID 3726696, 9 pages, 2022.

[3] Y. Liu, Y. Wang, and H. Li, “Enlightenment of world-class bay area industrial development to the construction of Guangdong-Hong Kong-Macao greater bay area,” *Journal of the Chinese Academy of Sciences*, vol. 35, no. 3, pp. 312–321, 2020.

[4] L. J. Zhang, S. J. Qu, and J. Dai, “Port capability evaluation from the perspective of supply chain,” *Discrete Dynamics in Nature and Society*, vol. 2021, Article ID 7633202, 12 pages, 2021.

[5] Z. L. Tai, J. Guo, Y. Guan, and Q. Shi, “Impact of COVID-19 on port production and operation based on system dynamics: a case study of shanghai port in China,” *Journal of Advanced Transportation*, vol. 2021, Article ID 9689391, 13 pages, 2021.

[6] Z. Y. Chen, “Port logistics function evaluation model based on entropy weight TOPSIS method,” *Discrete Dynamics in Nature and Society*, vol. 2022, Article ID 5006900, 10 pages, 2022.

[7] X. Zhao, X. W. Wang, and Q. L. Zhou, “Research on port cooperation mechanism under the strategic background of Maritime Silk Road,” *China soft science*, no. 12, pp. 5–14, 2016.

[8] J. L. Jiang, L. H. Lee, E. P. Chew, and C. C. Gan, “Port connectivity study: an analysis framework from a global container liner shipping network perspective,” *Transportation Research Part E: Logistics and Transportation Review*, vol. 73, no. 1, pp. 47–64, 2015.

[9] A. Marasco and A. Romano, “Inter-port interactions in the Le Havre-Hamburg range: a scenario analysis using a nonautonomous Lotka Volterra model,” *Journal of Transport Geography*, vol. 69, no. 5, pp. 207–220, 2018.

[10] J. Hintjens, “A conceptual framework for cooperation in hinterland development between neighbouring seaport authorities,” *Maritime Policy & Management*, vol. 45, no. 6, pp. 819–836, 2018.

[11] C. Yang, Q. Q. Li, Z. W. Hu et al., “Spatiotemporal evolution of urban agglomerations in four major bay areas of US, China and Japan from 1987 to 2017: e,” *Science of the Total Environment*, vol. 671, no. 6, pp. 232–247, 2019.

[12] H. Park and D. H. Kim, “A study on the strategies to improve the competitiveness of port hinterland focus on Busan Port & Gwangyang Port,” *Journal of Korea Research Association of International Commerce*, vol. 20, no. 2, pp. 59–73, 2020.

[13] E. Twrdy and M. Zanne, “Improvement of the sustainability of ports logistics by the development of innovative green infrastructure solutions,” *Transportation Research Procedia*, vol. 45, no. 4, pp. 11–29, 2020.

[14] Y. Fan, T. Y. Gao, and H. Qiao, “Research on competition and cooperation within port group based on Game Model—taking the Yellow Sea area as an example,” *System engineering theory and practice*, vol. 35, no. 4, pp. 955–964, 2015.

[15] X. Zhao, S. H. Gao, and Q. L. Zhou, “Research on the evolution of port system along the maritime Silk Road in the 21st century—based on logistics and Lotka Volterra model,” *Operations research and management*, vol. 27, no. 8, pp. 172–181, 2018.

[16] H. B. Kuang, S. J. Deng, and P. Jia, “Research on China’s port supply side reform based on port city separation,” *Scientific research management*, vol. 38, no. 4, pp. 54–65, 2017.

[17] L. Q. Guo and Z. Z. Yang, “Research on port integration method in multi-port area with the largest social welfare of internal transportation based on external transportation system,” *System engineering theory and practice*, vol. 38, no. 8, pp. 2098–2109, 2018.

[18] C. S. Lai, J. Lv, and T. H. Gao, “Research on revenue coordination mechanism of port supply chain based on optimized Shapley value[J],” *Practice and understanding of mathematics*, vol. 48, no. 2, pp. 49–56, 2018.

[19] M. Yu and M. Z. Xu, “Analysis on competitive strategy of inland river ports considering hinterland relationship[J],” *Transportation system engineering and information*, vol. 19, no. 5, pp. 28–34, 2019.

[20] M. Luo, L. Liu, and F. Gao, “Post-entry container port capacity expansion,” *Transportation Research Part B: Methodological*, vol. 46, no. 1, pp. 120–138, 2012.

[21] K. Wang, A. K. Y. Ng, J. S. L. Lam, and X. Fu, “Cooperation or competition? Factors and conditions affecting regional port governance in south China,” *Maritime Economics & Logistics*, vol. 14, no. 3, pp. 386–408, 2012.

[22] M. C. B. Cheng, D. Wang, and J. J. Wang, “A port-based evaluation framework of trade facilitation policies: case of Shenzhen and Hong Kong,” *Case Studies on Transport Policy*, vol. 6, no. 2, pp. 297–307, 2018.

[23] M. Z. Yu and J. Shan, “Game study on competition cooperation relationship in regional port group,” *Operations research and management*, vol. 23, no. 5, pp. 93–100, 2014.

[24] H. X. Xia, “Construction and application of container port alliance model based on game theory,” *Journal of Wuhan University of Technology*, vol. 30, no. 2, pp. 39–45, 2017.

[25] J. Wang, M. H. Zhang, and S. Q. Wang, “Shenzhen port competitiveness evaluation based on the construction of the guangdong-hong kong-macao greater bay area,” in *Proceedings of the 19th COTA International Conference of Transportation Professionals*, Nanjing,China, July 2019.

[26] M. T. Hannan and J. Freeman, “The population ecology of organizations,” *American Journal of Sociology*, vol. 82, no. 5, pp. 929–964, 1977.

[27] G. Buenstorf, “Self-organization and sustainability: energetics of evolution and implications for ecological economics,” *Ecological Economics*, vol. 33, no. 1, pp. 119–134, 2000.

[28] B. Han, P. F. Zhang, and H. B. Kuang, “Research on the strategy of port enterprise value chain division based on niche selection,” *System Engineering Theory and Practice*, vol. 38, no. 4, pp. 1024–1035, 2018.

[29] X. F. Wang and S. Liang, “Research on competition and cooperation of central ports in the Guangdong-Hong Kong-Macao greater bay area,” *Mathematical Problems in Engineering*, vol. 2022, Article ID 9589042, 9 pages, 2022.

[30] J. Sun, Y. Yuan, R. Yang, X. Ji, and J. Wu, “Performance evaluation of Chinese port enterprises under significant

environmental concerns: an extended DEA-based analysis," *Transport Policy*, vol. 60, pp. 75–86, 2017.

[31] X. F. Wang, S. Liang, and Z. J. Liao, "Integration, game, and sustainable development of shenzhen port based on governmental regulations," *Journal of Mathematics*, vol. 2022, Article ID 2583027, 11 pages, 2022.

[32] H. Q. Wang, "Comparison of effects of different control modes on port spatial structure and transaction efficiency—taking China's coastal port group as an example," *Economic Geography*, vol. 39, no. 1, pp. 104–112, 2019.

[33] J. X. Wang, *Interaction and Development of Chinese Port cities*, Southeast University Press, Nanjing, China, 2010.

[34] A. J. Lotka, *Elements of Physical Biology*, Williams and Wilkins Company, Philadelphia, PA, USA, 1925.

[35] V. Volterra, "Variazionie fluttuazionidel numerod' individual in specie animali conviventi," *Memorie Ricerca dell Academ ia Nazio-nale dei Lincei Serie*, vol. 6, no. 2, pp. 31–113, 1926.

[36] H. Chen, Q. N. Tu, and X. W. Dai, "Research on competitive mechanism and strategic choice of technical standards in high-tech enterprises—analysis Based on Ecological Lotka-Voterra interspecific competition model," *Scientific and technological progress and countermeasures*, vol. 32, no. 3, pp. 23–27, 2015.

[37] J. R. Tang, X. J. Li, and C. Du, "Research on the coordination path and co-governance of carbon reduction system in logistics industry—an Empirical Analysis Based on Lotka-Volterra model," *Soft Science*, vol. 30, no. 4, pp. 93–97, 2016.

[38] Z. G. Zhang, "Symbiotic coupling measurement model and criterion of forestry ecological security," *China population, resources and environment*, vol. 8, pp. 90–99, 2014.

[39] T. T. Zhou and W. P. Wang, "Study on the coordination of provincial industrial eco economic system based on Lotka Volterra model," *China management science*, vol. 22, no. 1, pp. 240–246, 2014.

[40] B. Sun and H. T. Yao, "Research on the competition mechanism of nuclear innovation network under the background of Globalization—simulation Analysis Based on improved LV-EG model," *Operations research and management*, vol. 25, no. 1, pp. 192–202, 2016.

[41] B. Lu, Y. J. Wen, and J. Xing, "Research on competition and cooperation strategy of ports around the Bohai Sea Based on TEI@ I methodology," *Management Review*, vol. 32, no. 7, pp. 246–257, 2020.

[42] Z. X. Zhou, *Research on Competition and Cooperation Relationship of Container Ports Based on Lotka Volterra model*, Chang'an University, Xi'an, China, 2015.

[43] B. Lu, W. Q. Qiu, J. Xing, and I. Moon, "Coordinated development strategy of China's coastal node ports and cities based on assessment of Belt and Road," *Systems Engineering-Theory & Practice*, vol. 40, no. 6, pp. 1627–1639, 2020.

[44] B. Lu and S. Y. Wang, "A comparative study of the container terminal operating efficiency between China and South Korea," *Management Review*, vol. 29, no. 5, pp. 175–182, 2017.

[45] B. Lu, X. F. Yang, and S. Y. Wang, "Port throughput forecasting model based on context change," *Management Review*, vol. 30, no. 1, pp. 195–201, 2018.