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Posted Date: June 13th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1686879/v1

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Research Article

Research on Competition and Cooperation of Central Ports in the Guangdong-Hong Kong-Macao Greater Bay Area Based on the Multi-group Lotka-Volterra Model

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Abstract: The construction of the Guangdong-Hong Kong-Macao Greater Bay Area requires the establishment of a comprehensive port cooperation mechanism. Coordination is key to port integration. This paper establishes a multi-group Lotka-Volterra model based on the theory of competition and cooperation to study the evolution of the relationships among Hong Kong Port, Shenzhen Port, and Guangzhou Port. The results show that the three major ports have predator-prey roles and form a symbiotic competition and cooperation ecological pattern. The extended Hotelling model is established to study the central ports’ spatial differences; the results show that whether it is the central port cooperation body or the entire central port group, the gains from Shenzhen Port–Guangzhou Port cooperation are greater than between either and Hong Kong Port for Guangdong-Hong Kong-Macao Greater Bay Area’s container business. The biggest competitor to Hong Kong Port in the container business is Guangzhou Port. Hong Kong Port will gain more from cooperation with Shenzhen Port and should strengthen such cooperation. The study provides quantitative support and reference for positioning the strategic development of the high-end shipping business in Hong Kong Port, the pilot free-trade port in Shenzhen Port, and the exploration of the Shenzhen-Hong Kong composite port, Guangzhou Port’s comprehensive shipping hub.

Keywords: evolutionary game theory; cooperation mechanism; central ports; multi-group Lotka-Volterra model; Guangdong-Hong Kong-Macao Greater Bay Area

Introduction

As a strategic hub node and infrastructure for foreign exchanges, ports are a barometer of economic development and play an extremely important role in maintaining the stability of the global industrial supply chain [1]. After years of construction and development, the port cluster in the Guangdong-Hong Kong-Macao Greater Bay Area has formed a coastal trade pattern centred on Hong Kong Port, Shenzhen Port, and Guangzhou Port and gradually improved the development of a global-oriented port, which belongs to the busiest and most intensive area in the global port range [2].
However, in recent years, with the emergence of the sluggish global shipping market during the post-crisis period, the problems existing in the Guangdong-Hong Kong-Macao Greater Bay Area’s ports are gradually being exposed, which, in turn, affects the long-term economic development of the entire region [3]. At present, the pace of economic restructuring in the Guangdong-Hong Kong-Macao Greater Bay Area is accelerating, and the requirements for the coordinated development of central ports are increasing. The development of central ports in the region is facing a new competition and cooperation game pattern. In the port cluster of the Guangdong-Hong Kong and Macao Greater Bay Area, each central port should not only improve its competitiveness through its own efficient operation and management but also consider cooperating with neighbouring central ports to form a transportation hub to compete with the external system. This could be accomplished if the cooperation between central ports is based more on competition, strengthening the complementary advantages of central port resources and the construction of coordination mechanism and realising the differentiated development of central ports.

At present, the ports of major countries and regions around the world have achieved great success through port models such as landlord ports. Moreover, they have taken into account local and overall interests through port integration and alliance, which has greatly promoted the healthy development of the port industry [4]. Although competition and cooperation among the port clusters in the Guangdong-Hong Kong-Macao Greater Bay Area has begun to take shape, it remains insufficient. Therefore, to deal with the problems of port surplus and resource waste, resource integration and integrated operation have become the key issues in the field of central port operation and management in the Guangdong-Hong Kong-Macao Greater Bay Area.

**Literature review**

In light of the current trend of port integration and collaborative development, the research on ports in the management field is mainly based on the perspective of competition and cooperation to establish and maintain a dynamic game relationship between participants [5]. To shift from pure confrontational competition to some degree of cooperation, the interaction between members must be adjusted from the perspective of the participants’ own development and social resource optimisation, and full play must be given to their own advantages in such cooperation, facilitating achievement of maximum gains [6–8]. Therefore, the research on the competition and cooperation game has become a hot topic in academic circles in China and abroad.

The existing research results regarding the port competition and cooperation game primarily include longitudinal and cross-sectional studies. The longitudinal research direction considers industry, while the cross-sectional research direction considers space. In terms of longitudinal studies of ports, Álvarez-SanJaime et al. [9] and Wan [10] examined the impact on regional port competition and cooperation and social welfare arising from the cooperation between ports and inland service providers. Pauline et al. [11] qualitatively analysed the contribution of port cooperation to social welfare, discussing the role of a central government in promoting port cooperation. For cross-sectional studies of ports, Zhao et al. [12-13] probed the competition and cooperation between ports along the 21st Century Maritime Silk Road and explored the stability of the port strategic alliance. Owing to the special spatial features of port competition, Hotelling models are widely applied. Yu Min et al. [14] based their study on a Hotelling model to analyse the income status of adjacent ports in inland river ports under different types of competition strategies. Considering the particularity in port
competition for market demand and coastal resources, Fan et al. [15] built a game model to examine the competition and cooperation among ports along the Yellow Sea. Kaselimi et al. [16] built a wharf duopoly game model with a Hotelling demand structure based on customer choice to investigate the impact that exclusive wharfs have on competition among port clusters. Along with economic downturn, port integration has accelerated in China. Song [17] carried out research on port integration based on the perspective of global supply chain and analysed the measures and impact of maritime logistics, while Kuang et al. [18] argued that supply-side reform in port-city separation can be used as a breakthrough point for port reform in China. From the perspective of maximised social welfare for internal transport in an outward transport system, Guo et al. [19] discussed port integration in a multi-port region, as exemplified by the ports in north-eastern China. In terms of port cooperation gains, Lai et al. [20-21] discussed the gains of the port competition and cooperation game as well as the coordination mechanism of the port supply chain. In addition, research on port competition and cooperation can also be found in Notteboom [22], Yu et al. [23], and Zongdaga et al. [24].

There is little research on the ports of the Guangdong-Hong Kong-Macao Greater Bay Area, and most are qualitative analysis. Few of the existing related quantitative studies were conducted primarily from the perspective of the Pearl River Delta before the proposal of the Guangdong-Hong Kong-Macao Greater Bay Area construction strategy. Considering local governments and container terminals in a port cluster, Yu et al. [25] built a mathematical model to examine the competition and cooperation game in a port cluster, as exemplified by the Hong Kong Port and Shenzhen Port in the Pearl River Delta. Using a two-stage game model, Luo et al. [26] investigated wharf price competition between the Port of Hong Kong and Shenzhen Port as well as port scale expansion. In terms of port cooperation research, Wang et al. [27] used a game-theoretical model to examine the influencing factors and port conditions in the Pearl River Delta, noting the importance of regional port alliances. In terms of port cooperation income research, Xia [28] conducted modelling analysis based on the container port alliance and obtained the distribution of cooperative game income and its functional solution. In addition, as exemplified by Shenzhen and Hong Kong, Michael et al. [29] quantitatively analysed the convenience of port trade.

In summary, there are few quantitative research results regarding the competition and cooperation game in the port integration of the Guangdong-Hong Kong-Macao Greater Bay Area. In view of the important position of the central port in the construction of the Guangdong-Hong Kong-Macao Greater Bay Area, based on the competition and cooperation game theory, this study models and analyses the central ports of the Guangdong-Hong Kong-Macao Greater Bay Area, represented by Hong Kong Port, Shenzhen Port, and Guangzhou Port. The study then explores the evolution of competition and cooperation relations among different central ports as well as the impact of cooperation strategies on port partners and the overall gains of the port, with the aim of providing quantitative support and a decision-making reference for the strategic development of central ports as well as the integration of ports in the Guangdong-Hong Kong-Macao Greater Bay Area.

Construction and analysis of a multi-centre port competition and cooperation game model
The interaction relationships among ports in a certain area have similar characteristics to the concept of population in ecology, and the main manifestation is that the number of the individual population will eventually reach the environmental capacity, which may lead to the competition of that population for resources, a predator-prey relationship between different populations, and mutually beneficial symbiosis [30]. The comprehensive influence of environmental and social factors, such as geographical location, the natural conditions of a given port, and government governance differences, leads to dynamic changes in port scale and port competitiveness in competition and cooperation. Therefore, the population-related theory can be applied to the study of the port competition and cooperation game.

The Lotka-Volterra model was first proposed to simulate the relationship between biological populations and was then gradually applied to the study of economic and social systems [31-32]. In view of the fact that the ports in the Guangdong-Hong Kong-Macao Greater Bay Area form a multi-centre port group, this paper introduces the multi-group Lotka-Volterra model into the study of the competition and cooperation game of central ports in the Guangdong-Hong Kong-Macao Greater Bay Area and establishes a multi-group competition and cooperation game model to discuss the game relationship among these ports.

Expression of the interaction relationship among central ports

The interaction among central ports in the Guangdong-Hong Kong-Macao Greater Bay Area can be expressed by the following mathematics:

1. Promotional effect: Central port $i$ and central port $j$ are positively correlated with changes in scale, which can be expressed as $i(+)$ $\rightarrow$ $j$;
2. Hindering effect: Central port $i$ and central port $j$ are negatively correlated with changes in scale, which can be expressed as $i(-)$ $\rightarrow$ $j$.

As a result, three different modes of the central port relationship are formed:

1. Mutualistic symbiosis among central ports, which can be expressed as $i(+) \rightarrow j$ and $j(+) \rightarrow i$
2. Competitive relations among central ports, which can be expressed as $i(-) \rightarrow j$ and $j(-) \rightarrow i$
3. Predator relationship among central ports, which can be expressed as $i(-) \rightarrow j$ and $j(+) \rightarrow i$

The competition and cooperation model for the three central ports in the Guangdong-Hong Kong-Macao Greater Bay Area is shown in Figure 1:
Construction of Lotka-Volterra model

Because the number of containers in the Guangdong-Hong Kong-Macao Greater Bay Area is limited, when ports with relatively balanced strength in the region compete for hinterland resources, they hinder each other’s development. In contrast, when the cooperation strategy is adopted, it promotes the development of each port’s port scale. Here, this study takes Hong Kong Port, Shenzhen Port, and Guangzhou Port, the three major central ports in the Guangdong-Hong Kong-Macao Greater Bay Area, as examples to conduct multi-port competition and cooperation game analysis. As this study focuses on the analysis of the interaction among central ports, it ignores the blocking effect of the port’s own scale growth and establishes a Lotka-Volterra model of the multi-population of central ports, as in formula (1):

$$
\begin{align*}
\frac{dh_1(t)}{dt} &= r_1 h_1 \left( 1 + \alpha_{12} \frac{h_2}{K_2} + \alpha_{13} \frac{h_3}{K_3} \right) \\
\frac{dh_2(t)}{dt} &= r_2 h_2 \left( 1 + \alpha_{21} \frac{h_1}{K_1} + \alpha_{23} \frac{h_3}{K_3} \right) \\
\frac{dh_3(t)}{dt} &= r_3 h_3 \left( 1 + \alpha_{31} \frac{h_1}{K_1} + \alpha_{32} \frac{h_2}{K_2} \right)
\end{align*}
$$

where $h_1(t)$, $h_2(t)$, $h_3(t)$ denotes the container throughput scale of Hong Kong Port, Shenzhen Port, and Guangzhou Port in year $t$, $r_i (i=1,2,3)$ denotes the container throughput growth rate of port $i$, $\alpha_{ij} (i=1,2,3) \ j=1,2,3$ denotes the coefficient of influence port $j$ has on port $i$, and $K_i (i=1,2,3)$ denotes the maximum container throughput of port $i$. Therefore, Eq. (1) was converted into Eq. (2) as follows:
\[
\begin{align*}
\frac{dh_1(t)}{dt} &= \beta_1 h_1 + \beta_{12} h_1 h_2 + \beta_{13} h_1 h_3 \\
\frac{dh_2(t)}{dt} &= \beta_{22} h_2 + \beta_{21} h_2 h_1 + \beta_{23} h_2 h_3 \\
\frac{dh_3(t)}{dt} &= \beta_{33} h_3 + \beta_{31} h_3 h_1 + \beta_{32} h_3 h_2
\end{align*}
\]

(2)

According to the mapping relationship between the grey derivatives and even logarithms, we obtained the following:

\[
\begin{align*}
h_1(t+1) - h_1(t) &= \beta_{11} \frac{h_1(t+1) + h_1(t)}{2} + \beta_{12} \left[ \frac{h_1(t+1) + h_2(t)}{2} \right] + \beta_{13} \left[ \frac{h_1(t+1) + h_3(t)}{2} \right] \\
&= \beta_{11} \frac{h_1(t+1) + h_1(t)}{2} + \beta_{12} \frac{h_1(t+1) + h_2(t)}{2} + \beta_{13} \frac{h_1(t+1) + h_3(t)}{2} \\
&= \beta_{11} \frac{h_1(t+1) + h_1(t)}{2} + \beta_{12} \frac{h_1(t+1) + h_2(t)}{2} + \beta_{13} \frac{h_1(t+1) + h_3(t)}{2} \\
&= \beta_{11} \frac{h_1(t+1) + h_1(t)}{2} + \beta_{12} \frac{h_1(t+1) + h_2(t)}{2} + \beta_{13} \frac{h_1(t+1) + h_3(t)}{2} \\
&= \beta_{11} \frac{h_1(t+1) + h_1(t)}{2} + \beta_{12} \frac{h_1(t+1) + h_2(t)}{2} + \beta_{13} \frac{h_1(t+1) + h_3(t)}{2} \\
&= \beta_{11} \frac{h_1(t+1) + h_1(t)}{2} + \beta_{12} \frac{h_1(t+1) + h_2(t)}{2} + \beta_{13} \frac{h_1(t+1) + h_3(t)}{2} \\
&= \beta_{11} \frac{h_1(t+1) + h_1(t)}{2} + \beta_{12} \frac{h_1(t+1) + h_2(t)}{2} + \beta_{13} \frac{h_1(t+1) + h_3(t)}{2} \\
&= \beta_{11} \frac{h_1(t+1) + h_1(t)}{2} + \beta_{12} \frac{h_1(t+1) + h_2(t)}{2} + \beta_{13} \frac{h_1(t+1) + h_3(t)}{2} \\
&= \beta_{11} \frac{h_1(t+1) + h_1(t)}{2} + \beta_{12} \frac{h_1(t+1) + h_2(t)}{2} + \beta_{13} \frac{h_1(t+1) + h_3(t)}{2}
\end{align*}
\]

(3)

\[
\begin{align*}
h_2(t+1) - h_2(t) &= \beta_{22} \frac{h_2(t+1) + h_2(t)}{2} + \beta_{21} \frac{h_2(t+1) + h_1(t)}{2} + \beta_{23} \frac{h_2(t+1) + h_3(t)}{2} \\
&= \beta_{22} \frac{h_2(t+1) + h_2(t)}{2} + \beta_{21} \frac{h_2(t+1) + h_1(t)}{2} + \beta_{23} \frac{h_2(t+1) + h_3(t)}{2} \\
&= \beta_{22} \frac{h_2(t+1) + h_2(t)}{2} + \beta_{21} \frac{h_2(t+1) + h_1(t)}{2} + \beta_{23} \frac{h_2(t+1) + h_3(t)}{2} \\
&= \beta_{22} \frac{h_2(t+1) + h_2(t)}{2} + \beta_{21} \frac{h_2(t+1) + h_1(t)}{2} + \beta_{23} \frac{h_2(t+1) + h_3(t)}{2} \\
&= \beta_{22} \frac{h_2(t+1) + h_2(t)}{2} + \beta_{21} \frac{h_2(t+1) + h_1(t)}{2} + \beta_{23} \frac{h_2(t+1) + h_3(t)}{2} \\
&= \beta_{22} \frac{h_2(t+1) + h_2(t)}{2} + \beta_{21} \frac{h_2(t+1) + h_1(t)}{2} + \beta_{23} \frac{h_2(t+1) + h_3(t)}{2} \\
&= \beta_{22} \frac{h_2(t+1) + h_2(t)}{2} + \beta_{21} \frac{h_2(t+1) + h_1(t)}{2} + \beta_{23} \frac{h_2(t+1) + h_3(t)}{2}
\end{align*}
\]

(4)

\[
\begin{align*}
h_3(t+1) - h_3(t) &= \beta_{33} \frac{h_3(t+1) + h_3(t)}{2} + \beta_{31} \frac{h_3(t+1) + h_1(t)}{2} + \beta_{32} \frac{h_3(t+1) + h_2(t)}{2} \\
&= \beta_{33} \frac{h_3(t+1) + h_3(t)}{2} + \beta_{31} \frac{h_3(t+1) + h_1(t)}{2} + \beta_{32} \frac{h_3(t+1) + h_2(t)}{2} \\
&= \beta_{33} \frac{h_3(t+1) + h_3(t)}{2} + \beta_{31} \frac{h_3(t+1) + h_1(t)}{2} + \beta_{32} \frac{h_3(t+1) + h_2(t)}{2} \\
&= \beta_{33} \frac{h_3(t+1) + h_3(t)}{2} + \beta_{31} \frac{h_3(t+1) + h_1(t)}{2} + \beta_{32} \frac{h_3(t+1) + h_2(t)}{2} \\
&= \beta_{33} \frac{h_3(t+1) + h_3(t)}{2} + \beta_{31} \frac{h_3(t+1) + h_1(t)}{2} + \beta_{32} \frac{h_3(t+1) + h_2(t)}{2} \\
&= \beta_{33} \frac{h_3(t+1) + h_3(t)}{2} + \beta_{31} \frac{h_3(t+1) + h_1(t)}{2} + \beta_{32} \frac{h_3(t+1) + h_2(t)}{2}
\end{align*}
\]

(5)

When \( t = 1, 2, L, n \), the related data were substituted into the above equations, yielding the matrix equations \( A_m = \lambda_i \beta_i (i = 1, 2, 3) \); for example, for Shenzhen Port, the matrix equation is \( A_{2n} = \lambda_2 \beta_2 \), and

\[
\lambda_2 = \begin{bmatrix}
\frac{h_2(1) + h_2(2)}{2} & \frac{h_2(1) + h_2(2)}{2} & \frac{h_2(1) + h_2(2)}{2} \\
\frac{h_2(2) + h_2(3)}{2} & \frac{h_2(2) + h_2(3)}{2} & \frac{h_2(2) + h_2(3)}{2} \\
\frac{h_2(n-1) + h_2(n)}{2} & \frac{h_2(n-1) + h_2(n)}{2} & \frac{h_2(n-1) + h_2(n)}{2}
\end{bmatrix}
\]

\[
A_{2n} = \begin{bmatrix}
\frac{h_2(1) - h_1(1)}{2} & \frac{h_2(1) - h_1(1)}{2} & \frac{h_2(1) - h_1(1)}{2} \\
\frac{h_2(2) - h_1(2)}{2} & \frac{h_2(2) - h_1(2)}{2} & \frac{h_2(2) - h_1(2)}{2} \\
\frac{h_2(n) - h_1(n)}{2} & \frac{h_2(n) - h_1(n)}{2} & \frac{h_2(n) - h_1(n)}{2}
\end{bmatrix}
\]

(6)

Using the least square method, we obtained the following:

\[
\beta_2 = \left( \lambda_2^T \lambda_2 \right)^{-1} \lambda_2^T A_{2n}
\]

Data analysis

By substituting the container throughput data of the three central ports in the Guangdong-Hong Kong-Macao Greater Bay Area from 2007 to 2018 and then repeating this step, we obtained the matrix equation parameters \( \beta_j = \hat{\beta}_j \) for \( i = 1, 2, 3; j = 1, 2, 3 \) as shown in Table 1.
### Table 1 Parameter estimates

<table>
<thead>
<tr>
<th>$\hat{\beta}_{ij}$</th>
<th>HK $i = 1$</th>
<th>SZ $j = 2$</th>
<th>GZ $j = 3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HK $i = 1$</td>
<td>---</td>
<td>1.144E-04</td>
<td>-7.48E-05</td>
</tr>
<tr>
<td>SZ $i = 2$</td>
<td>-3.278E-05</td>
<td>---</td>
<td>1.135E-06</td>
</tr>
<tr>
<td>GZ $i = 3$</td>
<td>2.061E-05</td>
<td>-2.086E-05</td>
<td>---</td>
</tr>
</tbody>
</table>

From the conversion relationship between the parameters $\hat{\beta}_{ij} = (i = 1, 2, 3; j = 1, 2, 3)$ and the influence coefficient $\alpha_{ij}$ of the port, we observed that the positive and negative of the parameters $\hat{\beta}_{ij}$ and $\alpha_{ij}$ are consistent. Therefore, this can be used to analyse the relationship among the three central ports. Table 1 shows that the three central ports in the Guangdong-Hong Kong-Macao Greater Bay Area have the following relationships during the development process: $\hat{\beta}_{12} > 0$ indicates that Shenzhen Port has a positive effect on Hong Kong Port, while $\hat{\beta}_{21} < 0$ indicates that Hong Kong Port has a negative effect on Shenzhen Port, meaning that they have a predator-prey relationship in which Hong Kong Port is the predator and Shenzhen Port is the prey; $\hat{\beta}_{23} > 0$ indicates that Guangzhou Port has a positive effect on Shenzhen Port, while $\hat{\beta}_{32} < 0$ indicates that Shenzhen Port has a negative effect on Guangzhou Port, meaning that they have a predator-prey relationship in which Shenzhen Port is the predator and Guangzhou Port is the prey; and $\hat{\beta}_{31} < 0$ indicates that Guangzhou Port has a negative effect on Hong Kong Port, while $\hat{\beta}_{13} > 0$ indicates that Hong Kong Port has a positive effect on Guangzhou Port, meaning that they have a predator-prey relationship in which Guangzhou Port is the predator and Hong Kong Port is the prey.

The interaction diagram of the three central ports is as follows in Figure 2:

![Figure 2 Interaction diagram of the three central ports’ container business in the Guangdong-Hong Kong-Macao Greater Bay Area](image-url)
A symbiotic ecosystem is formed among the three central ports, but has predator-prey relationships, and this interaction forms an unstable equilibrium, as shown in Figure 3 below \((i, j = 1,2,3; i \neq j)\).

![Figure 3 The two-by-two unstable equilibrium of the three central ports in the Guangdong-Hong Kong-Macao Greater Bay Area](image)

At this time, within the scope of region I, the container throughput of central port \(h_j(t)\) cannot continue to grow while that of central port \(h_i(t)\) continues to grow; within the scope of region II, the container throughput of central port \(h_i(t)\) cannot continue to grow while that of central port \(h_j(t)\) continues to grow. In this case, the competition between central port \(i\) and central port \(j\) cannot form a stable state, and both are likely to win in the competition. At this time, the interests of the central ports are not entirely consistent. This unstable balance may lead to the consequences of excessive competition and potentially develop into a situation of vicious and extreme competition. In view of the influence of the institutional environment, economic hinterland, comprehensive strength, and other factors relevant to the three central ports of the Guangdong-Hong Kong-Macao Greater Bay Area, it is necessary to intervene at the national level to promote port integration. The integration should be based on market-oriented orientation and supplemented by government-level macro guidance.

The competition faced by ports is primarily market demand competition, and is due to competition in spatial location and route arrangements. In view of this, this paper primarily discusses the competition and cooperation game caused by the difference of port spatial location, and a Hotelling model is a classic game model for studying spatial difference competition. Considering that this study examines the multi-port competition and cooperation game, the model is extended to a two-dimensional space to better reflect to the actual problem.

**Construction and analysis of an extended Hotelling model**

**Construction of an extended Hotelling model**
Taking the three central ports in the Guangdong-Hong Kong-Macao Greater Bay Area as an example, this paper develops abstract positioning based on the natural geographical location of the central port, assuming that Hong Kong Port is located at \((1,0)\), Shenzhen Port is located at \((1,\mu)\) and \(0 < \mu < 1\), Guangzhou Port is located at \((1,1)\), as shown in Figure 4 below:
Combined with the geographical location of the central ports in the Guangdong-Hong Kong-Macao Greater Bay Area, the market demand assumption shows that the hinterland of the central ports is evenly distributed in the rectangle composed of (0,0), (0,1), (2,1), (2,0), the transportation cost is positively related to the transportation distance, and the unit transportation cost is $\eta$.

The three central ports in the Guangdong-Hong Kong-Macao Greater Bay Area compete through pricing and providing loading and unloading services. We assume that $a_i$ is the price of central port $i, i=1,2,3,$ and $F_i(a_1,a_2,a_3)$ is the demand function of that central port. In view of the close geographical location and similar natural conditions of the three central ports, we consider there to be no significant difference in the service cost of each central port, which means that for cost $c$, the following exist: $c_1 = c_2 = c_3$.

Suppose there are two coordinate positions, $s_1, s_2$; when the source of goods comes from $(0,s_1)$, Hong Kong Port $(1,0)$ will undertake the loading and unloading tasks; when the source of goods comes from $(s_1,s_2)$, Shenzhen Port $(1,\mu)$ will undertake the loading and unloading tasks; and when the source of goods comes from $(s_2,1)$, Guangzhou Port $(1,1)$ will undertake the loading and unloading tasks.

Based on this, the market shares of the three central ports are as follows:

$$F_1 = 2\int_0^{s_1} \int_1^{s_2} dxdy = 2s_1$$

$$F_2 = 2\int_{s_1}^1 \int_1^{s_2} dxdy = 2(s_2 - s_1)$$

$$F_3 = 2\int_{s_2}^1 \int_1^{s_1} dxdy = 2(1-s_2)$$

According to the Hotelling model, we obtain the following:

$$\begin{align*}
a_1 + \eta s_1 &= a_2 + \mu \eta - \eta s_1 \\
a_2 + \eta(s_2 - \mu) &= a_3 + \eta(1-s_2)
\end{align*}$$

We further obtain:


\begin{align*}
  s_1 &= \frac{1}{2}\mu + \frac{a_2 - a_1}{2\eta} \\
  s_2 &= \frac{1}{2}(1 + \mu) + \frac{a_3 - a_2}{2\eta}
\end{align*}

(11)

In view of the fact that this paper focuses on the cooperation behaviour based on the above competition, which is primarily reflected in the cooperation gains among different central ports in the Guangdong-Hong Kong-Macao Greater Bay Area and the overall changes in the gains of a given central port when different central ports cooperate. Considering the actual situation of the current development of the three central ports, this paper primarily discusses the change in gains when Shenzhen Port competes with Hong Kong Port on the basis of cooperation between Shenzhen Port and Guangzhou Port, the change in gains when Shenzhen Port competes with Guangzhou Port on the basis of cooperation between Shenzhen Port and Hong Kong Port, and the change in overall gains when different central ports cooperate.

Assuming that Shenzhen Port and Guangzhou Port compete with Hong Kong Port on the basis of cooperating in pricing \((\mu_2 = \mu_3)\), at this time, the market demands of the central ports are as follows:

\begin{align*}
  F_1 &= 2\int_0^{s_1} \int_1^2 dx dy = 2s_1 = \mu + \frac{a_2 - a_1}{\eta} \\
  \text{The total market demand of Shenzhen Port and Guangzhou Port is:}
  F_{23} &= 2\int_0^{s_1} \int_1^2 dx dy = 2(1 - s_1) = 2 - \frac{a_2 - a_1}{\eta}
\end{align*}

(12) (13)

The gains function of the central port is:

\begin{align*}
  \pi_1 &= (a_1 - c)F_1 = (a_1 - c)\left(\mu + \frac{a_2 - a_1}{\eta}\right) \\
  \pi_2 &= (a_2 - c)F_{23} = (a_2 - c)\left(2 - \mu - \frac{a_2 - a_1}{\eta}\right)
\end{align*}

(14)

By deriving the above gains function, we obtain the following results:

\begin{align*}
  \frac{\partial \pi_1}{\partial a_1} &= \mu + \frac{a_2 - 2a_1 + c}{\eta} = 0 \\
  \frac{\partial \pi_{23}}{\partial a_2} &= 2 - \mu - \frac{2a_2 - a_1 - c}{\eta} = 0
\end{align*}

(15)

We also obtain:

\begin{align*}
  \mu \eta + a_2 - 2a_1 + c &= 0 \\
  2\eta - \mu \eta - 2a_2 + a_1 + c &= 0
\end{align*}

(16)

Therefore, the optimal price, market demand, and gains function of the central ports can be obtained as follows:

\begin{align*}
  a_1^* &= \frac{\eta}{3}(\mu + 2) + c \\
  \quad a_2^* = \frac{\eta}{3}(4 - \mu) + c
\end{align*}

(17)
Similarly, assuming that Shenzhen Port and Hong Kong Port compete with Guangzhou Port on the basis of cooperative pricing \((\mu_1 = \mu_2)\), the gains of the central ports at this time are obtained as follows:

\[
\pi_{12} = \frac{\eta}{18} (\mu^2 + 6\mu + 9),
\]

\[
\pi_3' = \frac{\eta}{18} (\mu^2 - 6\mu + 9).
\]

**Model analysis**

According to the Hotelling model formula, the gains of the three central ports under the independent development state can be calculated as follows:

\[
\pi_1' = \frac{\eta}{32} (4\mu^2 + 4\mu + 1), \quad \pi_2' = \frac{\eta}{4}, \quad \pi_3' = \frac{\eta}{32} (4\mu^2 - 12\mu + 9)
\]

It can be proved that the gains from cooperation between central ports are greater than those of ports acting under a strategy of competition, \(\pi_{23} > (\pi_{2} + \pi_{3}').\) When some central ports adopt a cooperation strategy, the gains of the non-cooperative central ports are also greater than those under competitive conditions, \(\pi_1 > \pi_1',\) and the cooperation strategy can improve the level of gains for the entire central port group, \((\pi_1 + \pi_{23}) > (\pi_1 + \pi_{2} + \pi_{3}'),\) though these basic proofs will not be carried out here. This paper primarily discusses the comparison of the gains of different central ports adopting cooperation strategies as well as the changes in the overall gains of the central port group.

**Proposition 1:** In regard to the container business, the cooperation gains of Shenzhen Port and Guangzhou Port are greater than those of Hong Kong Port.

**Certificate 1:**

\[
\pi_{23} - \pi_{12} = \frac{\eta}{9} (\mu^2 - 8\mu + 16) - \frac{\eta}{18} (\mu^2 + 6\mu + 9)
\]

\[l_i = \pi_{23} - \pi_{12}.'\] By deriving the above functions, it can be concluded that \(l_i = \frac{\eta}{9} (\mu - 11)\) because of \(\mu \in (0,1).\) \(\eta > 0;\)

therefore, \(l_i < 0, l_i\) is a monotonically decreasing function on the interval, and

\[\lim_{\mu \to 1} \frac{\eta}{9} > 0.\] It can be concluded that \(\pi_{23} > \pi_{12}.\) This shows that the cooperation gains of Shenzhen Port and Guangzhou Port in the field of the container business are greater than the cooperation gains of Shenzhen Port and Hong Kong Port in the same field, as shown in Figure 5 below:
Figure 5 Comparison of container business cooperation gains between two different central ports

Proposition 2: When Shenzhen Port and Guangzhou Port cooperate in the field of the container business, the overall gains of the three central ports are greater than those of Hong Kong Port.

Certificate 2: Denotes \( l_2 = (\pi_1 + \pi_{23}) - (\pi'_{12} + \pi'_{3}) \); thus, \( l_2 = \frac{\mu^2 - 4\mu + 11}{9} \eta \). By deriving the above functions, it can be concluded that \( l'_2 = \frac{\eta}{9} (2\mu - 4) \) because of \( \mu \in (0,1) \), \( \eta > 0 \); therefore, \( l'_2 < 0 \), \( l_2 \) is a monotonically decreasing function on the interval, and \( \lim_{\mu \to 1^+} l_2 = \frac{8}{9} \eta > 0 \). It can be concluded that \( (\pi_1 + \pi_{23}) > (\pi'_{12} + \pi'_{3}) \). This indicates that when Shenzhen Port and Guangzhou Port cooperate in the container business, the overall gains of the three central ports are greater than those of Shenzhen Port and Hong Kong Port, as shown in Figure 6 below:

Figure 6 Comparison of container business overall gains in the cooperation between two different central ports
Research conclusions

The port is the key fulcrum and core hub of the 21st-Century Maritime Silk Road and plays an important role in the construction of the One Belt One Road. Based on the multi-group Lotka-Volterra model, this paper studies the evolution of the competition and cooperation game among the central ports (Hong Kong Port, Shenzhen Port and Guangzhou Port) of the Guangdong-Hong Kong-Macao Greater Bay Area. The results show that the three central ports exist in a symbiotic ecosystem and play predator-prey in relation to each other within the Guangdong-Hong Kong-Macao Greater Bay Area port group. The extended Hotelling model not only proves that cooperation among central ports can net more gains than can competition but also further confirms the changes in the cooperation gains of different central ports as well as the overall gains of all central ports. In terms of developing the container business, the biggest competitor of Hong Kong Port is Guangzhou Port, rather than Shenzhen Port. Hong Kong Port will gain more from cooperation with Shenzhen Port. Therefore, it should take the initiative to strengthen its cooperation with Shenzhen Port. In the process of cooperating with Guangzhou Port, Shenzhen Port will obtain higher returns (for example, Shenzhen and Guangzhou signed the deepening strategic cooperation framework agreement in September 2019), while Guangzhou Port is actively strengthening its cooperation with Hong Kong Port (Guangzhou Port has already taken practical action to support Hong Kong Port container transportation; from January to November 2018, the container throughput between Guangzhou Port and Hong Kong Port was 2.7 million TEUs, which accounts for 38% of the container throughput of Guangzhou Port foreign trade). This is all in line with the current situation of cooperation among the three major centres. Competition and cooperation coexist among the three centres; cooperation should be carried out on the basis of competition, and at the same time, competition should also be carried out on the basis of cooperation. Therefore, facing the pressure of port development, the central ports of the Guangdong-Hong Kong-Macao Greater Bay Area must implement a differentiated development strategy. As the next outlet for transformation, Hong Kong Port must rely on its resource advantages to vigorously develop high-end shipping businesses such as shipping finance and shipping insurance. As the link between Hong Kong Port and Guangzhou Port, Shenzhen Port should actively explore cooperation with Hong Kong Port in the high-end shipping business, explore a Shenzhen-Hong Kong combination port and free trade port, and strengthen its cooperation with Guangzhou Port in the container business. Based on the current situation, Guangzhou Port will further develop its container business and build a regional integrated international shipping hub.

This paper establishes a competition and cooperation game model for central ports in the Guangdong-Hong Kong-Macao Greater Bay Area to illustrate the symbiotic relationship between central ports. Therefore, prior to port integration and strategic development positioning, the interaction among central ports and the evolutionary trend should be fully considered, and on this basis, overall coordination can be achieved to maximise gains. While moderately curbing excessive competition, it is necessary to emphasise the establishment of a stable and orderly cooperation mechanism among central ports. We recommend that a Guangdong-Hong Kong-Macao Greater Bay Area Port Alliance be established to reduce administrative divisions. At a higher level, the government should make overall arrangements for the construction and development of central ports in the Guangdong-Hong Kong-Macao Greater Bay Area. To ultimately achieve mutual benefits, they should also strengthen the consensus regarding cooperation among central ports and, under the premise of
integration, eliminate the adverse influence of monopoly after completing functional zoning; moreover, they should fully utilise the competitive advantage of each central port and establish a coordination mechanism, trust mechanism, and benefit distribution mechanism among central ports.

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 Guangdong Province. Data are available at: (https://zenodo.org/record/6417050#.Yk1LrcgmG-U), these data are available free of charge.

Author Contributions

Conceptualization: Xuanfei Wang, data curation: Shan Liang, formal analysis: Xuanfei Wang, writing—original draft: Xuanfei Wang, software: Shan Liang, writing—review and editing: Xuanfei Wang, Shan Liang and Zhenjie Liao. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Funding Statement

This study was financed by the philosophy and social sciences of Guangdong Province in the 13th Five-year Period [GD20XGL06]; the philosophy and social science programme of Guangzhou in the 14th Five-year Period [2021GZGJ73]; the educational science programme of Guangdong in the 13th Five-year Period [2019GXJK084]; the philosophy and social science programme of Guangzhou in the 13th Five-year Period [2018GZGJ57]; a grant from the Guangzhou Huashang College[2022HSDS02].

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