Allometric Relationship and Development Potential Comparison of Ports in a Regional Cluster：A case study of ports in the Pearl River Delta in China

Abstract: The development potential of a regional port cluster is subject to both the internal and external factors influencing port development. Port cargo throughput is the most important internal factor, while the value of import and export is regarded as the most significant external factor. The growth rate of import and export value is disproportional with the one of port cargo throughput. This paper, using a case study of the ports in China's Pearl River Delta, aims to develop a comprehensive development potential evaluation system for a regional port cluster to measure the allometric relationship between the two factors of port throughput and import and export value. The new finding reveals that the value of import and export has a higher impact on port development potential than port cargo throughput. In addition, in terms of the value of import and export, Shenzhen has the highest development potential, while Zhuhai Port has the highest potential as far as port cargo throughput is concerned. Finally, using the comprehensive development potential evaluation system, Shenzhen Port is evaluated to have the best comprehensive port development potential. The development potential evaluation of the ports in a regional port cluster will offer useful insights for the regional port company groups and relevant governmental authorities to make scientific decisions on port development and planning, and to rationally coordinate their development and minimize unfair competition.

Keywords: regional port cluster, cargo throughput, value of import and export, allometric growth, port development potential

1. Introduction

The fast development of the port industry in coastal China is a result of the large value of import and export and port cargo throughput in the past decades. However, the development prospect of the ports in China has been facing many risks such as the external sluggish global and regional economy situation and the internal saturating port scale. For the purpose of quantitatively evaluating the development potential of the ports in a regional port cluster, an allometric growth model and its growth matrix are used in this study by taking into account the factors of internal port throughput and external import and export value. The allometric relationship between different ports and their corresponding development potential in future can greatly aid port policy makers to get an overall insight into the evolution mechanism of a regional port cluster and rationally plan port development blueprints. The study is also of great significance to steer the port policy orientation, strategy propelling and corresponding development of a regional port cluster to eventually achieve the coordinated, orderly and harmony development of a regional port cluster.

The paper adopts an allometric growth model and its growth matrix to study the allometric relationship of the ports in a regional port cluster and quantitatively evaluate their comprehensive development potential. Allometry refers to the disproportional development and growth relationship between two factors. Huxley and Teissier coined the term “allometry” in 1936, and used the term in the field of relative growth (Huxley & Teissier, 1936). Naroll and Von Bertalanffy (1956) discovered the allometry relationship in biology. In the past several decades, scholars introduced this concept into the research of social and economic systems, unveiling the inherent logical connections between the different allometric coefficients impacted by different factors (Lee, 1989; Chen & Zhou, 2004; Zhang & Yu, 2010; Chen, 2017). This paper investigates the ports in the the Pearl River Delta port cluster in China, including Hongkong Port as the center, and Guangzhou Port, Shenzhen Port and Zhuhai Port as major marine transportation hubs (MOT, 2006). The geographical locations and distribution of these ports are shown in Figure 1. This paper collects and describes a full set of data on the two factors of the port cargo throughput and value of import and export as the most influential internal and the external factors of port development potential, respectively.

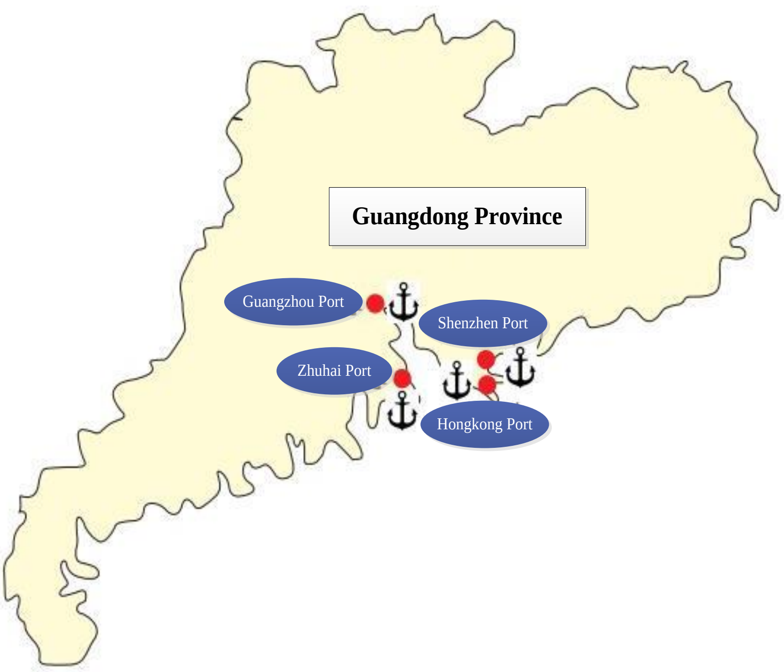

Figure 1 Geographical Locations and Distribution of the Main Ports in the Pearl River Delta

The rest of the paper is organized as follows. After the literature review, the paper discloses the knowledge gaps in Section 2, and defines the research aim and objectives. In Section 3, the allometric theory is explained in detail firstly and then the allometric growth model and the allometric growth matrix are used to develop the methodology of a comprehensive port development potential evaluation system. In Section 4, the paper using the ports in the Pearl River Delta to demonstrate the methodlogy in Section 3, describes the evaluations of the relative growth potential between the internal and external factors, the growth potential of various ports against each of the above two factors and the comprehensive development potential of the ports with respect to the two factors simultaneously. In addition, some constructive opinions on the development directions and focuses of each port in the future are put forward according to the findings from Section 4. Conclusions are summarized and future research directions are suggested in Section 5.

2. Literature Review

Regional port clusters are experiencing increasingly fierce competition due to the stagnant global economic situation and the saturating port resources, which renders a high risk affecting the future development of the port industry. The analysis of the influencing factors of port development and the evaluation on port development competitiveness have been a focus of the global maritime research community for long time. However, only very few paid attention to the port development of a regional port cluster from the perspective of allometric relationship. In addition, current port evaluation studies are dominated by port competitiveness rather than development potential.

The attribution analysis of port development often presents the most interest of port enterprises, governmental authorities/regulators and researchers in the relevant fields. The attribution of port development can be primarily divided into three types: (1) regime, policy and regulation; (2) economic situation; (3) port production capacity. Representative studies on regime, policy and regulation include but not limited to the followings. De Langen and Chouly (2004) studied the port clusters in the downstream areas of Rotterdam, Durban and Mississippi to look at the differences of their corresponding hinterland access systems. Subsequently, De Langen and Visser (2005) extended the study on the port cluster in the downstream areas of Mississippi and found that the reducing market share of throughput was caused by the less efficient or even inefficient cluster systems. Homosombat et al. (2016) provided several constructive policy recommendations on the cooperation between the port of Shenzhen with the port of Hongkong to improve their hinterland access. Woo et al. (2018) studied environment-related policies of ports and found that environment policies exerted a negative impact on port economy in a short term, but they were helpful to improve the competitiveness of the ports in the future. Chang et al. (2018) paid attention to the correlation between Emission Control Areas (ECA) regulations and the operation efficiency of European ports. Studies from the perspectives of regimes, policies and regulations dominate the attribution analysis of port development, but most of them were associated with qualitative rather than quantitative analysis. Studies from the perspectives of economic analysis and port production capacity were the most conducted in the quantitative methods. For instance, Song and Van Geenhuizen (2014) studied the contributions of port infrastructure investment in China to regional economic growth. Wilmsmeier and Monios (2015) put forward that regional economic status could influence the competitiveness of ports. Anguibi (2015) pointed out that economic performance, foreign investment and domestic investment all played an important role in the productivity of ports. Bottasso et al. (2018) found that the infrastructure construction of ports in Brazil was closely related to the robust growth of export trade of Brazil. Aldrete et al. (2018) suggested to concentrate foundations on port infrastructure construction in Texas. Chen et al. (2018) took Shanghai port as an example to study the relative growth of port throughput and urban population, and put forward that throughput was a key contributor to port development.

The methods of establishing quantitative evaluation systems for ports are dominated by a DEA model with other models as a supplement. Park and De (2015) discovered that an alternative DEA model was a potential method of evaluating the overall efficiency of a port. In the same year, Barros and Athanassiou (2015) also studied the efficiency of sea ports in Greece and Spain based on the same model. Nguyen et al. (2016) applied a bootstrapped DEA model to evaluate the top 43 ports in Vietnam. Rajasekar and Deo (2018) used a DEA additive model to discover that Jawaharlal Nehru Port significantly outperformed other Indian ports in terms of operation efficiency. Mo et al. (2018) evaluated the port logistics competitiveness based on DEA and the results showed that there was a waste of resource in Shenzhen port in terms of its input and output several years ago. Other port evaluation methods included the fuzzy model, the optimization model and the game theory. Gao et al. (2018) used a Fuzzy-AHP and ELECTRE III to study the competitiveness of Quanzhou port and found its relatively weak infrastructure and high port costs were the main reasons for lagging behind among the other four ports in the region. Abbasi and Pishvaee (2018) investigated the location of dry ports in Iran by an optimization model. The alternative duopoly game method was used in port competitiveness research (Zhuang et al., 2014). Cui and Notteboom (2018) studied the effects of port authorities' objective orientation and the service differentiation among competing or cooperating ports by the game theory model. Ha et al. (2017a) used an evidential reasoning approach to establish a comprehensive port competitive index and applied it to evaluate the major container ports in Korea, while Ha and Yang (2017b) extended the evidential reasoning approach by incorporating ANP and DEMATAL methods to investigate the interdependence among the attributes influencing port competitiveness. Following their investigation on Korean container port performance, Ha et al., (2018) applied an importance-performance analysis approach to pioneer the quantitative analysis of port performance from a multiple-stakeholder perspective. Although the above models are capable of evaluating the competitiveness of ports in a quantitative manner, they have not yet fully explored the evaluation of port development potential within the context of a regional port cluster from the allometric relationship perspective. They are therefore not able to further specify the differentiated growth between different factors influencing port development potential.

In summary, in the literature relating to port performance and competitiveness, few studies evaluated the port growth differences from the perspective of allometric relationship between the ports in a regional port cluster. It is necessary to develop a new evaluation system to investigate the allometric relationship of the most important factors influencing port performance to rationally quantify the development potential of ports. Therefore, this paper is committed to filling these gaps and addressing the following two issues: (1) to make a comprehensive consideration of the contribution by external economic factors and internal port production factors to the port development potential in a regional port cluster. (2) to develop a new quantitative evaluation system for port development potential to offer port planning guidance for a regional port cluster and to facilitate the coordinated and orderly development of the port industry in a region.

3. Methodology

A regional port cluster, as a system consisting of numerous individual ports, whose development potential is subject to both the overall competitiveness of the cluster and the growth rates of the individual ports. The paper adopts an allometric growth model to measure the disproportionate growth relationship between the internal (i.e. cargo throughput) and external (i.e. economic prosperity) factors on port development. Using the model, the paper works out the allometric coefficient to determine whether an allometric relationship exists or not. On the premise of existence of an allometric relationship, the growth model is expanded to its growth matrix based on the above calculated coefficients, and the eigenvectors of the matrix are used for studying the relative growth potential of the investigated ports. Finally, the comprehensive development potential system for the ports in a regional cluster is constructed, using the internal factor, the external factor,their relative growth potential and the growth potential of various ports against the internal and external factors.

3.1 Research framework

This paper studies the allometric relationship of a regional port cluster and evaluates the port development potential by achieving the following three objectives: (1) to identify whether an allometric relationship exists between the port cargo throughput (internal factor) and the value of import and export (external factor). (2) to calculate the eigenvalues of the allometric growth matrix, including the development potential of the two factors and of the various ports against the factors. (3) to set up a comprehensive development potential system for the ports in a regional port cluster. The framework and the involved specific steps are described in Figure 2.

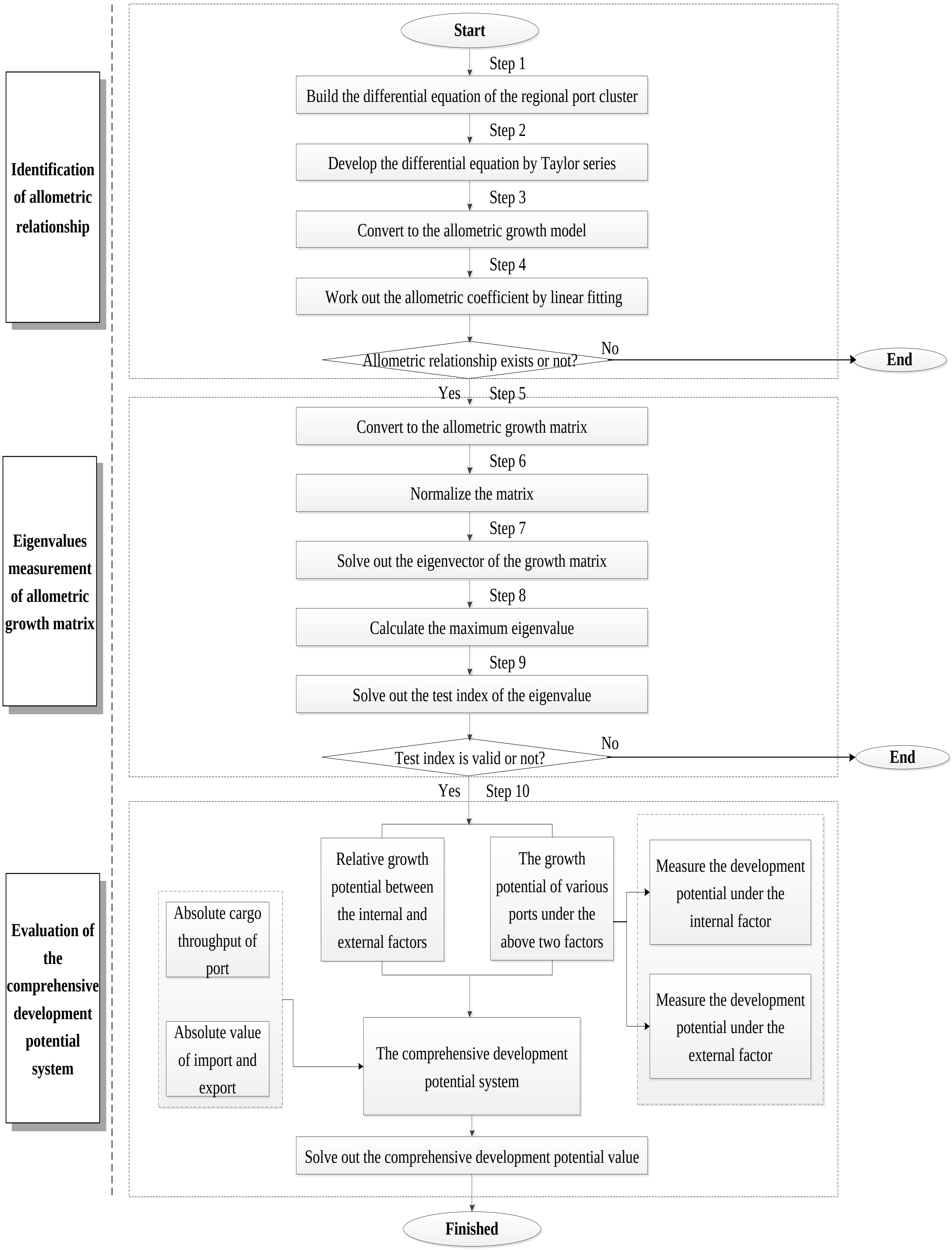

Figure 2 Framework for Evaluation of Allometric Relationship and Development Potential of the Ports in a Regional Port Cluster

3.2 Model formulation

The process of the model can be divided into three parts: an allometric relationship study, the calculation of the eigenvalues of a growth matrix and the construction of a comprehensive port development potential system. Through the allometric relationship study, the allometric coefficients can be calculated as the foundations of the growth matrix. Based on the growth matrix, the eigenvalues of the investigated ports against the two factors can be estimated, which are used as the basis of the comprehensive port development potential system. The detailed process of the model is described as follows:

Step 1: Build the differential equation of i th port under the impact of the k factor:

$$\frac{dx_{ik}}{dt} = f(x_{1k}, x_{2k}..., x_{nk}) \tag{1}$$

i ranges from 1 to n. n is the total number of individual ports in the investigated regional port cluster. k is only a letter symbol with no numeric value, which representing a specific factor.

Step 2: Develop Formula (1) by Taylor series and convert it to Formula (2):

$$\frac{dx_{ik}}{dt} = a_{ik} x_{ik} \tag{2}$$

The differential equations of other ports under the impact of k factor can be developed in a similar way, as shown below:

$$\frac{dx_{jk}}{dt} = a_{jk} x_{jk} \tag{3}$$

j ranges from 1 to n and isn't equal to i. When the allometric relationship between any two ports under the same factor is studied, Formula (2) and (3) can be transformed to Formula (4) and (5) as shown below, by removing the symbol k.

$$\frac{dx_i}{dt} = a_i x_i \tag{4}$$

$$\frac{dx_j}{dt} = a_j x_j \tag{5}$$

Step 3: Formula (4) divided by Formula (5) is converted into Formula (6).

$$\frac{dx_i}{dt} = \frac{a_i}{a_j} \frac{x_i}{x_j} \frac{dx_j}{d_t} \tag{6}$$

$\frac{a_i}{a_j}$ is the relative allometric coefficient between the i th and the j th port against the same factor, and it is often simplified to a_{ij}. Therefore, Formula (6) can be further converted to Formula (7).

$$\frac{dx_i}{dt} = a_{ij} \frac{x_i}{x_j} \frac{dx_j}{d_t} \tag{7}$$

Subsequently, dt can be eliminated to get $dx_i / x_i = a_{ij}\, dx_j / x_j$. Then it can be converted to be presented by a natural logarithmic form, as shown below:

$$\ln(x_i) = a_{ij} \ln(x_j) + C \tag{8}$$

C is an unknown constant. Supposing $\ln(\beta) = C$, Formula (8) can be further converted to an allometric growth model as follows:

$$x_i = \beta x_j^{a_{ij}} \tag{9}$$

Step 4: Calculate a_{ij}, the allometric coefficient. It can be obtained by the linear fitting of Formula (8). The paper identifies whether the allometric relationship exists according to the allometric coefficient α_{ij}. The allometric relationship specifically has three different forms (Lee, 1989; Chen, 2010; Chen, 2014) as shown below:

(1) When α_{ij} > 1, the growth rate of the dependent variable is faster than that of the independent variable, presenting the positive allometric growth.

(2) When α_{ij} < 1, the growth rate of the dependent variable is slower than that of the independent variable, presenting the negative allometric growth.

(3) When α_{ij} = 1, the growth rate of the dependent variable is in line with that of the independent variable, presenting the non-allometric growth.

Step 5: Build an n order allometric growth matrix M, and a_{ij} is the element of the i th row and the j th column as Formula (10):

$$M = \left[a_{ij}\right]_{n\times n} = \begin{bmatrix} a_1/a_1 & a_1/a_2 & \dots & a_1/a_n \\ a_2/a_1 & a_2/a_2 & \dots & a_2/a_n \\ \vdots & \vdots & & \vdots \\ a_n/a_1 & a_n/a_2 & \dots & a_n/a_n \end{bmatrix} = \left[a_i/a_j\right]_{n\times n} \tag{10}$$

Step 6: Normalize the allometric growth matrix by column with reference to Formula (11):

$$\chi_{ij} = a_{ij} \Big/ \sum_{i=1}^{n} a_{ij} \ \ (i, j = 1, 2, \cdots n) \tag{11}$$

Step 7: The allometric growth matrix M and its eigenvector A meet the following Formula (12):

$$MA = nA \tag{12}$$

According to $\left[a_i/a_j\right]_{n\times n}\left[a_1 \quad a_2 \quad \cdots \quad a_n\right]^T = n\left[a_1 \quad a_2 \quad \cdots \quad a_n\right]^T$, so the eigenvector is $A = \left[a_1 \quad a_2 \quad \cdots \quad a_n\right]^T$, representing the set of the development growth rates of the ports against a selected factor.

Add the above results by row to get a new vector $\hat{\omega}_i = \sum_{j=1}^{n} \chi_{ij}$. Then normalize them using $\omega_i = \hat{\omega}_i \Big/ \sum_{i=1}^{n} \hat{\omega}_i$ to get the basic element of the eigenvector matrix as shown below:

$$W = \left[\omega_1 \quad \omega_2 \quad \cdots \quad \omega_n\right] \tag{13}$$

Step 8: Calculate the maximum eigenvalue:

$$\gamma_{\max} = \frac{1}{n}\sum_{i=1}^{n} \frac{(MW)_i}{\omega_i} \tag{14}$$

Step 9: Test the $Index$ value using Formula (15) to validate the obtained eigenvalues.

$$Index = \frac{\left|\gamma_{\max} - n\right|}{n-1} \tag{15}$$

Identification rule: the eigenvalue is deemed to be valid when the test index value is close to zero.

Step 10: Solve the port development potential based on the eigenvectors of the allometric growth matrix.

Definition: the cargo throughput matrix of a port in a regional port cluster is defined as

$X_1 = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \end{bmatrix}$. $W_1 = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1n} \end{bmatrix}$ is the normalized eigenvector of the allometric growth matrix under the internal factor dimension. Then we can measure the development potential of various ports from the perspective of the internal factor as Formula (16):

$$y_1 = X_1 W_1^{\mathrm{T}} \tag{16}$$

Definition: value of import and export of a port in the regional port cluster is defined as $X_2 = \begin{bmatrix} x_{21} & x_{22} & \cdots & x_{2n} \end{bmatrix}$. $W_2 = \begin{bmatrix} w_{21} & w_{22} & \cdots & w_{2n} \end{bmatrix}$ is the normalized eigenvector of the allometric growth matrix under the external factor dimension. Then we can measure the development potential of various ports from the perspective of the external factor as Formula (17):

$$y_2 = X_2 W_2^{\mathrm{T}} \tag{17}$$

Definition: the absolute values of a port against both the internal and the external factors are defined as a vector $V = \begin{bmatrix} v_1 & v_2 \end{bmatrix}$, then the total potential of a port in a regional port cluster is calculated using Formula (18):

$$\mathrm{Potient}_{\mathrm{total}} = YV^{\mathrm{T}} = \begin{bmatrix} y_1 & y_2 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = v_1 y_1 + v_2 y_2 \tag{18}$$

Finally, a comprehensive port development potential evaluation system can be constructed and the comprehensive development potential of the i th port in its regional port cluster is shown below:

$$\mathrm{Potient}_{\mathrm{i}} = \frac{x_{1\mathrm{i}} \omega_{1\mathrm{i}} v_1 + x_{2\mathrm{i}} \omega_{2\mathrm{i}} v_2}{\mathrm{Potient}_{\mathrm{total}}} \tag{19}$$

The larger the value is, the higher the port's potential.

4. Case Study and Result Analysis

4.1 Data collection

This paper takes the regional port cluster of the Pearl River Delta in China as a real case to 1) demonstrate the feasibility of the proposed model in practice and 2) analyse the development potential of the ports in the Pearl River Delta port cluster, in which a few world class ports (e.g. Shenzhen and Hong Kong) have high competition, requiring rational guide on their future developments. In the cluster, the large-scale ports, representing the sea ports with annual 15 million metric tons cargo throughput by the Ministry of Transport of the People's Republic of

China (MOT 2016) include Hong Kong Port, Zhuhai Port, Shenzhen Port and Guangzhou Port. The index of port cargo throughput is the most important internal factor on port development potential, and the index of value of import and export attached to these port cities is the most classical external factor used for port development potential analysis. The data of the ports with reference to the two factors are collected from the yearbooks of Guangdong province and Hong Kong special administrative region from 1997 to 2016. The data of port cargo throughput and value of import and export of these port cities are shown in Figures 3 and 4, respectively. As shown, Guangzhou Port enjoys the most robust growth in port cargo throughput, having excellent performance against the internal factor. From the perspective of the external factor, Shenzhen outperforms the other three port cities in terms of the value of import and export, but its value had a downward trend.

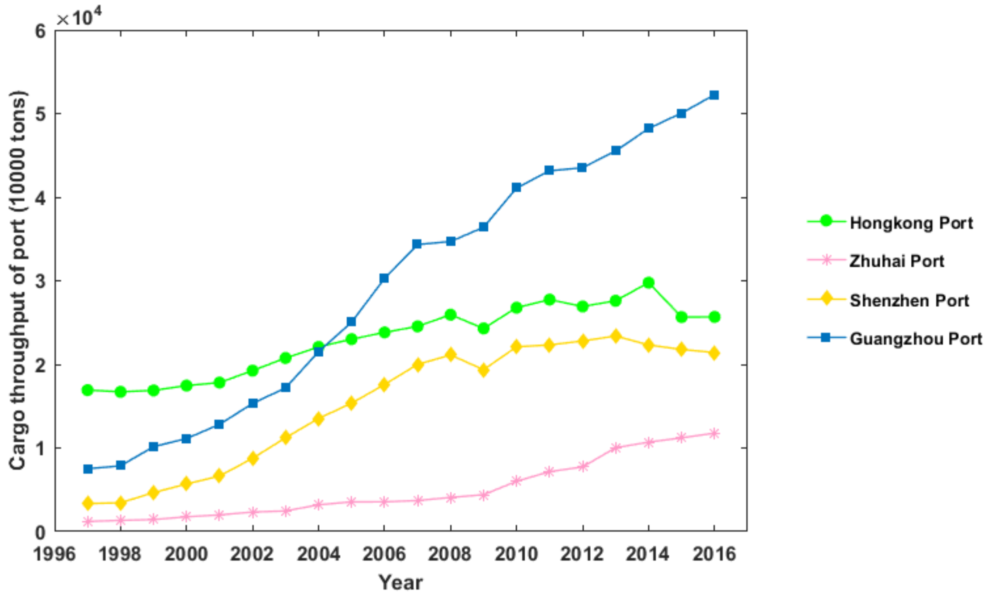

Figure 3 Cargo Throughput of the Ports in the Pearl River Delta Port Cluster

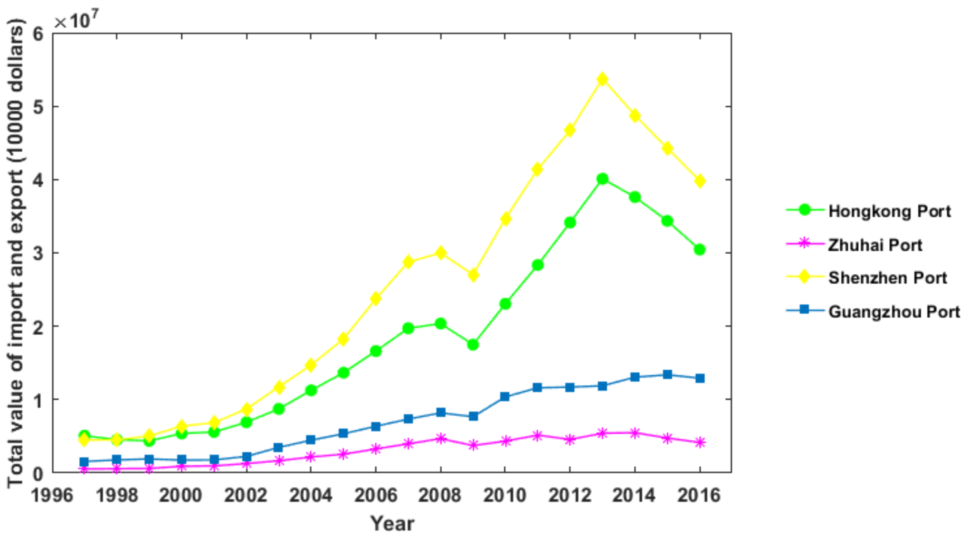

Figure 4 Value of Import and Export of the Port Cities in the Pearl River Delta

4.2 Model establishment

This paper uses an allometric growth model to compare the growth rates of port cargo throughput (i.e. internal factor) with the import and export values of port cities (i.e. external factor), revealing the importance of the two factors in port development. The allometric model is then expanded to formulate an allometric growth matrix, to measure the relative growth potential between the internal and external factors, the growth potential of the investigated four ports against the two factors, and to construct an integrated comprehensive potential system of the cluster ports.

4.2.1 Relative growth potential between the internal and external factors

This paper regards the port cargo throughput and value of import and export of port cities as the most significant internal and external factor on port development potential, respectively. Based on Figure 2 (the methodology), the first step is to measure the relative growth potential between the above two factors.

First, the total port cargo throughput T_{total} from 1997 to 2016 is accumulated based on the annual data of the cluster ports. The total values of import and export of the port cities V_{total} in the 20 years are also aggregated.

According to Step 1 to Step 3, we constructed the allometric growth model based on the total port cargo throughput and the total trade value, as Formula (20) shown:

$$T_{\text{total}} = \beta \times V_{\text{total}}{}^{\alpha} \tag{20}$$

β is an unknown constant, and α is the allometric coefficient used to identify whether the two factors have the allometric relationship or not, depending on the fact that the relationship meets the positive one or the negative one.

Then we take the natural logarithms of both sides of Formula (20):

$$\ln(T_{\text{total}}) = \alpha \times \ln(V_{\text{total}}) + \ln(\beta) \tag{21}$$

Fitting Formula (21) linearly, we work out the slope α as shown in Figure 5:

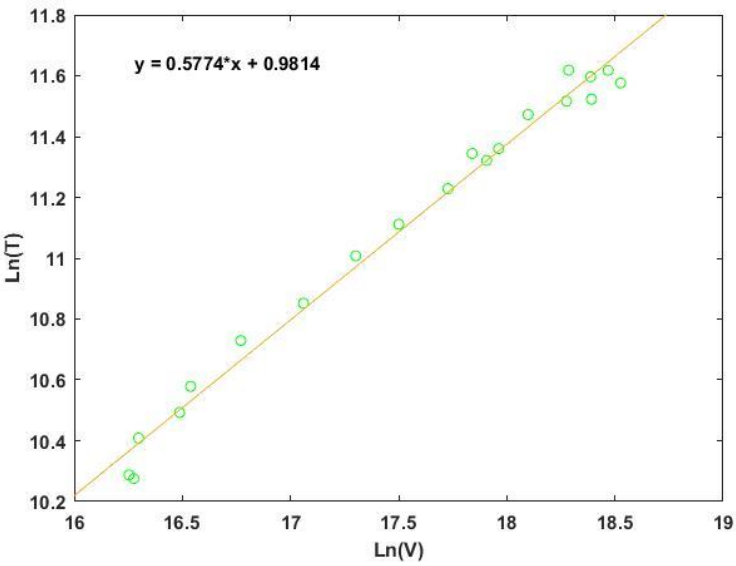

Figure 5 Allometric Relationship Between the Internal and External Factors

The allometric relationship model of the internal and external factors is constructed:

$$\ln(T_{\text{total}}) = 0.5774 \times \ln(V_{\text{total}}) + 0.9814 \tag{22}$$

We switch the independent and dependent variables, to establish Formula (23):

$$\ln(V_{\text{total}}) = 1.7099 \times \ln(T_{\text{total}}) - 1.4549 \tag{23}$$

The allometric coefficients of Formula (22) and (23) are 1.7099 and 0.5774, respectively. The results disclose that there is a significant allometric relationship between the internal and external factors in the Pearl River Delta port cluster.

According to Step 6, we calculate the eigenvalues of port cargo throughput and the value of import and export as 0.3675 and 0.6325, respectively. It means that the growth rate of the external factors is 1.7 times more than that of the internal factor, meaning the external factor has a more significant effect on port development in the future.

4.2.2 The growth potential of various ports against the two factors

In the previous stage, we calculated the two eigenvalues of the internal and external factors, then the growth potential of various ports is measured with respect to each of the two factors.

4.2.2.1 The growth potential of ports against the internal factor

According to Step 1 to Step 3, we construct the allometric model between any two ports with respect to port cargo throughput as follows:

$$T_A = \beta \times T_B{}^{\alpha} \tag{24}$$

T_A represented the cargo throughput of Port A and T_B represented that of Port B.

We take the natural logarithms of both sides of Formula (24):

$$\ln(T_A) = \alpha \times \ln(T_B) + \ln(\beta) \tag{25}$$

β is an unknown constant and α is the allometric coefficient. Fitting Formula (25) linearly, we work out the slope α of each of the 6 pairs of any two ports in the cluster as shown in Figure 6:

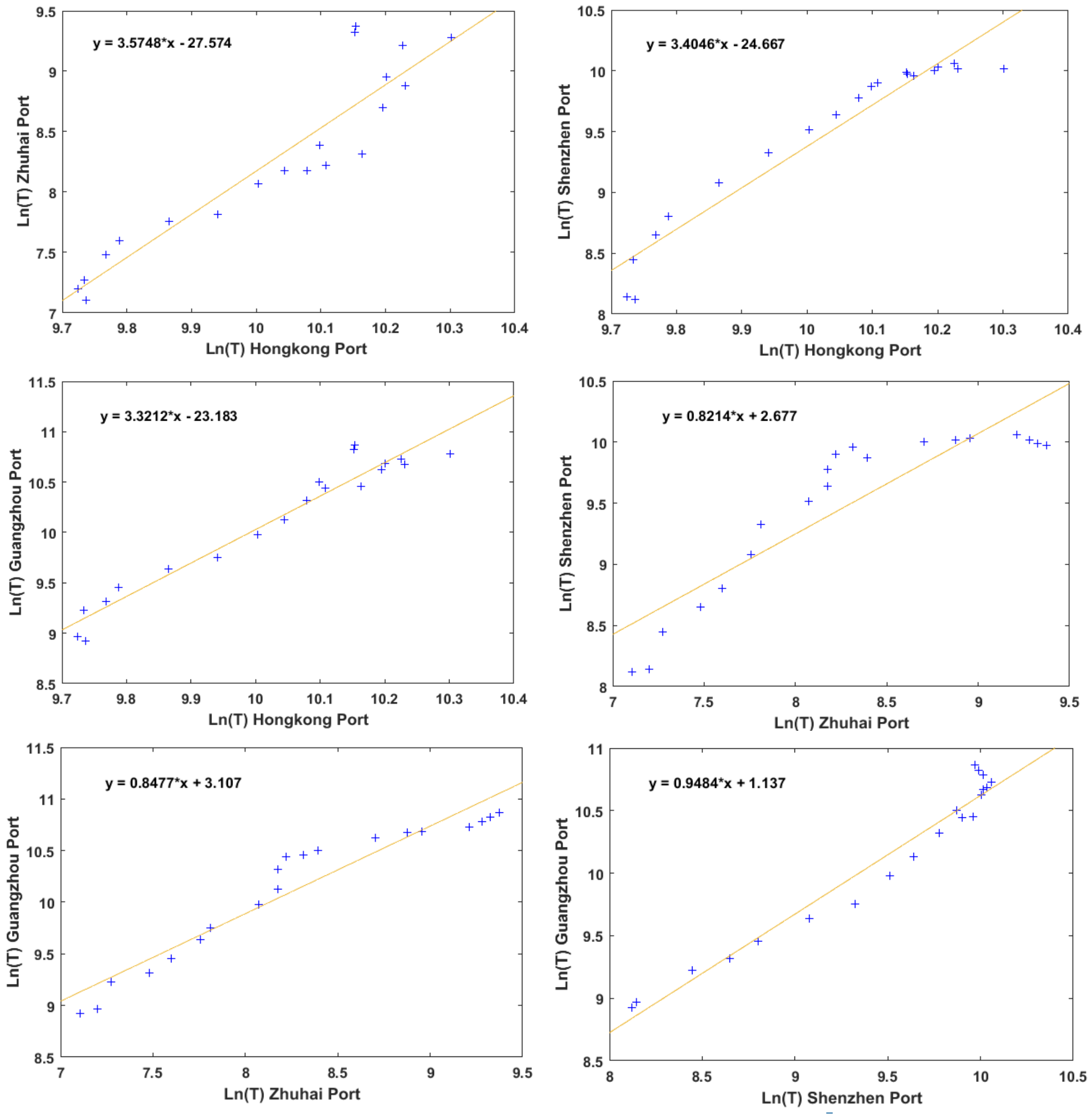

Figure 6 Allometric Model of Any Two Ports in Internal Dimension

We use the obtained allometric coefficients α and follow Step 5 to develop an allometric growth matrix as shown in Table 1:

Table 1 Allometric Growth Matrix with Respect to Port Cargo Throughput

A \ B	Hongkong Port	Zhuhai Port	Shenzhen Port	Guangzhou Port
Hongkong Port	1.0000	0.2411	0.2740	0.2854
Zhuhai Port	3.5748	1.0000	0.9801	1.0802
Shenzhen Port	3.4046	0.8214	1.0000	1.0127

Guangzhou Port	3.3212	0.8477	0.9484	1.0000

According to Step 7, we normalize the above matrix as shown in Table 2:

Table 2 Normalized Allometric Growth Matrix with Respect to Port Cargo Throughput

A \ B	Hongkong Port	Zhuhai Port	Shenzhen Port	Guangzhou Port
Hongkong Port	0.0885	0.0828	0.0856	0.0845
Zhuhai Port	0.3163	0.3436	0.3060	0.3197
Shenzhen Port	0.3013	0.2822	0.3123	0.2998
Guangzhou Port	0.2939	0.2913	0.2961	0.2960

We then calculate the eigenvalues of each port as shown in Table (3).

Table 3 The Growth Potential of Every Port with Respect to Port Cargo Throughput

Port Cargo Throughput	Hongkong Port	Zhuhai Port	Shenzhen Port	Guangzhou Port
Eigenvector value	0.0853	0.3214	0.2989	0.2943

To test the validity of the above eigenvectors, we compute the maximum eigenvalue $\gamma_{\max} = 3.8515$ using Formula (14) and the test index is obtained as 0.0495 according to Formula (15). Because the test index was close to 0, the eigenvalues are valid.

4.2.2.2 The growth potential of ports against the external factor

In a similar way, the eigenvalues of the four ports with regards to the values of import and export of the port cities are obtained, as shown in Table (6).

Table 6 The Growth Potential of Every Port with Regards to the Values of Import and Export

External Dimension	Hong Kong	Zhuhai	Shenzhen	Guangzhou
Eigenvector value	0.2378	0.2479	0.2687	0.2455

Using Formula (14) and (15), the test index is 0.0164, proving the eigenvalues are valid.

As shown in Figure 8, the eigenvalue of Zhuhai Port is 0.3214, the most highest value in terms of the internal factor, which meant Zhuhai Port had the best port development potential along with the increase of the port cargo throughput. From the perspective of trade value, the eigenvalue of Shenzhen is 0.2687, the highest value in the external factor, meaning Shenzhan Port has the best port development potential along with the increase of the value of import and export.

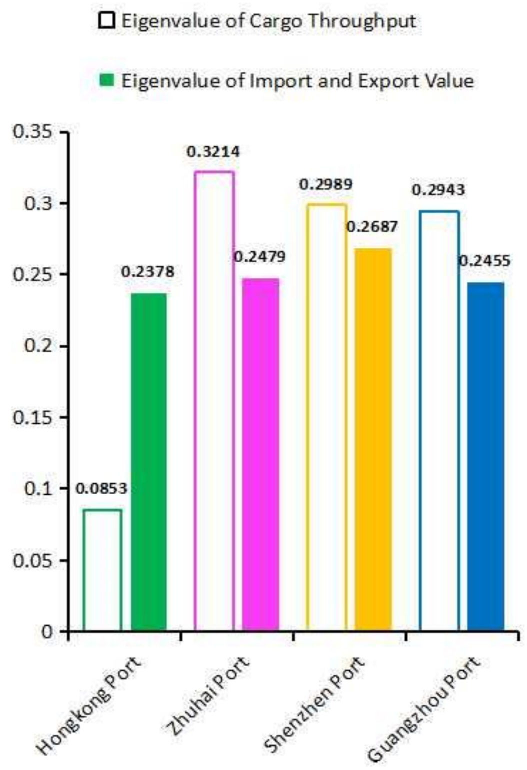

Figure 8 The Growth Potential of Ports against the Internal and External Factors

4.2.3 A comprehensive development potential system for ports

The results from Sections 4.2.1 and 4.2.2 are used as the input data to construct the comprehensive development potential system for the four ports in the Pearl River Delta cluster.

Table 7 Input Data from Sections 4.2.1 and 4.2.2

	Absolute cargo throughput (10,000 t)	The potential in terms of the internal factor	Absolute trade value (10,000 US dollars)	The potential in terms of the external factor
Relative potential between the internal and external factors	0.3675		0.6325	

Hong Kong Port	25,673	0.0853	30,456,830	0.2378
Zhuhai Port	11,779	0.3214	4,173,161	0.2479
Shenzhen Port	21,417	0.2989	39,843,892	0.2687
Guangzhou Port	52,254	0.2943	12,930,895	0.2455

According to Formula (16) to (19), we use the input data in Table 7 to evaluate the comprehensive development potential scores of all the four ports and the results are shown in Figure 9.

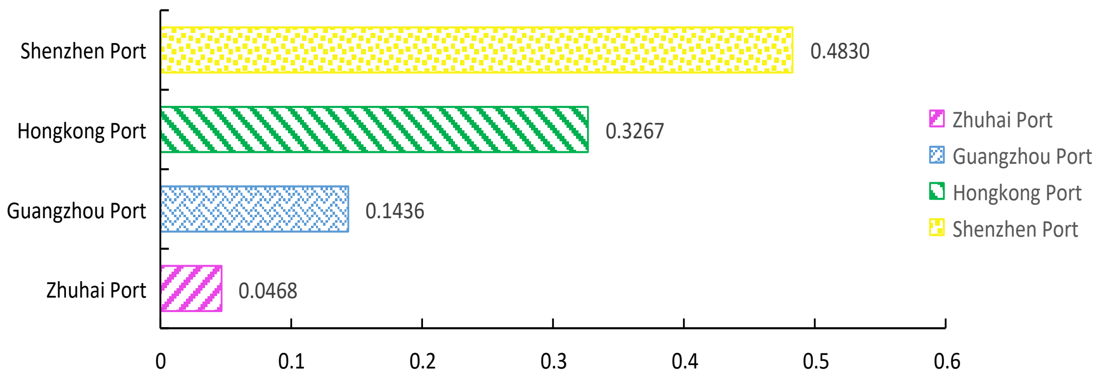

Figure 9 Comprehensive Development Potential Scores of the Four Ports

In the Pearl River Delta port cluster, Shenzhen Port has the highest potential score of 0.4830, while Zhuhai Port has the lowest one of 0.0468. The port development potential scores from Figure 9 indicate that Shenzhen Port has the highest develop potential in future when both cargo throughput and trade value are concerned simultaneously.

4.3 Result analysis

This paper studies the allometric relationship between the ports in the the Pearl River Delta port cluster in China and evaluates their port development potential for setting out the corresponding development planning of each involved port in the future.

In terms of port cargo throughput (internal factor), Zhuhai Port has the highest eigenvalue, indicating that the port owns an attraction to absorb cargo throughput from the other three ports in the Pearl River Delta. For that reason, It is suggested that Zhuhai Port needs to leverage its geographic location at the Westest place among the other three ports (see Figure 1), and it can be used as the first calling port by the ships from abroad to increase its cargo throughput. Meanwhile, it can also develop the river shipping with the economic advantage of the river-ocean combined transportation in the Pearl River Delta. While Hong Kong Port has the lowest eigenvalue, indicating that the port attracts less cargo. It suggests that Hong Kong Port needs to develop new strategies to attract high-value cargo for offsetting the loss of cargo throughput.

In terms of trade value (i.e. the external factor), Shenzhen has the highest eigenvalue, indicating that the city owns an attraction to absorb trade value from the other three cities in the Pearl River Delta. We suggest that Shenzhen needs to further open up and respond to the opinions of the Shenzhen municipal people's government on speeding up the port development and setting up a free trade zone at the end of 2020 (Shenzhen Government Online, 2015). While Hong Kong also has the lowest eigenvalue with respect to the external dimension, indicating that the city is losing its attraction to international trade, which can be explained by the intense competition between Hong Kong with the rising new-built free trade zones in mainland China.

A comprehensive development potential system has been constructed, and the comprehensive development potential values of the four ports also have been evaluated. Shenzhen Port has the highest development potential value at 0.4830, closely followed by Hong Kong Port at 0.3267. The lag of the potential in Hong Kong Port can be attributed to the saturation of its urban land-use area and its relative slow growth of economy. In contrast, Shenzhen Port has an excellent development potential owing to its larger traffic capacity which creates the attraction of port cargo throughput. For example Shenzhen is connected to two main national railway networks, and 107 national highways, and the river-ocean combined transportation of Shenzhen also has a great development prospect. In addition, the excellent development potential of Shenzhen Port can be attributed to the continuous open-up of its market which creates the attraction of new trade. For example Shenzhen Port has established the friendly relationship with more than 20 international ports (Shenzhen Transportation Bureau 2017). The Shenzhen Shekou free trade zone established in 2015 boosts the attraction of trade volumes, and the advanced high-tech industry in Shenzhen also facilitates the growth of the trade volume (Chen, et al., 2018; Chen, et al., 2018). The comprehensive development potential values of Guangzhou Port and Zhuhai Port lag behind Shenzhen Port and Hong Kong Port. It is suggested that Guangzhou Port needs to take advantage of the high demand on the cruise market in Guangzhou and set up Guangzhou International Cruise

Home Port (Xinhuanet 2018). We suggest that Zhuhai Port needs to be invested more, especially on port infrastructures and hinterland area, because it has the highest eigenvalue in terms of port cargo throughput.

5. Conclusions and Future Research

The development potential of the ports in a regional port cluster is mainly subject to the synergism between port cargo throughput and value of import and export. The port cargo throughput represents the typical internal factor on the development potential of ports, while the value of import and export represents the typical external factor on ports. Both of them play significant roles on port development in the future, though their influence levels are different. The paper uses an allometric growth model to measure the growth rates of the internal and external factors, and the growth rates of each port with respect to cargo throughput or import and export value in the Pearl River Delta. Then an allometric growth matrix is established to evaluate the development potential values of the ports based on the above growth rates. The study finds that (1) the value of import and export has a significantly higher impact on port development potential than port cargo throughput; (2) as fart as cargo throughput is concerned, Zhuhai Port has the best port development potential; while in terms of import and export value, Shenzhan Port has the best port development potential; (3) the results from a comprehensive port development potential system shows that Shenzhen Port has the highest score in the regional port cluster of the Pearl River Delta, indicating that the port will take advantage of cargo throughput and trade value to promote its development to the most extent in the future. These findings offer useful insights to port policy makers and port enterprises, enabling a better coordination and division of businesses between the ports in the regional port cluster to eventually promote the orderly, concerted and favorable development of ports.

It is an innovative attempt to apply the allometric growth model and the allometric growth matrix for analyzing the internal and external factors influencing the development of ports in a regional port cluster and evaluating the comprehensive port development potential system. Further studies can be conducted from the following three aspects in the future. First, the allometric growth model can be improved by adopting the nonlinear methods and a better weight-allocation solution. Secondly, the probabilistic method can be introduced into the allometric growth model to facilitate precise evaluation of the development potential system. Thirdly, the internal and external factors on port development can be expanded, involving more factors from economy, environment, policy-making perspectives.

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