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Comparative analysis of port efficiency in Yangtze River Delta and Pearl River Delta: a meta Dynamic D.D.F. approach

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ABSTRACT

The Yangtze River Delta and Pearl River Delta are two regions with the highest level of economic development in China, and their port development is at the forefront of the country. This study measures the efficiency of 23 major ports in the two deltas from 2010 to 2018 using the meta Dynamic Directional Distance Function (D.D.F.) model and discusses the technology gap and the reasons for inefficiency of the ports. The research results show that 80% of the ports in these two deltas are inefficient. The Yangtze River Delta's port efficiency is higher than that of the Pearl River Delta, but the internal efficiency difference of the Yangtze River Delta port cluster is more significant. The efficiency ranking of most ports is inconsistent under the meta-frontier (M.F.) and group frontier (G.F.), and the average technology gap ratio (T.G.R.) of ports in the Pearl River Delta gradually exceeds that in the Yangtze River Delta. The inefficiency of ports in the Pearl River Delta is caused by input factors, and the inefficiency of ports in the Yangtze River Delta is also related to the containerisation level.

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1. Introduction

With the globalisation of the world economy, more than 80% of the global commodity trade is processed through ports (Dong et al., 2019; Suárez-Alemán et al., 2016), making them an important node in the global trade and logistics supply chain. As a large manufacturing country, China plays an increasingly important role in global economic development, and its ports are important strategic resources. At present, the throughput of seven ports in China ranks among the world's top 10, but the development level of Chinese ports is still uneven. With the ports developing to a certain stage and their growth rate slowing down, problems like waste of resources, overlapping hinterlands, and insufficient output occur. To deal with these problems,

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the function of modern ports must shift from traditional sections to high-end positions in the value chain (Jiang et al., 2017). Since port efficiency substantially influences the whole supply chain and affects the nation's trade performance and the economy (Blonigen & Wilson, 2007), improving port efficiency has been an essential breakthrough for transforming port development mode and enhancing regional comparative advantage.

There have been significant researches into port efficiency, and the most commonly used methods are data envelopment analysis (D.E.A.) and stochastic frontier approach (S.F.A.). Standard D.E.A. is more widely used because it can process multiple inputs and outputs without presetting functions and parameters, avoiding subjective factors. However, the standard D.E.A. assumes that all evaluated decision-making units (D.M.U.s) are at the same technical level, which may lead to inaccurate estimates. By considering the heterogeneity of ports and the dynamic changes in their efficiency, the meta Dynamic Directional Distance Function (D.D.F.) method can overcome the defect of the standard D.E.A. method to make the port efficiency estimation more accurate.

From the perspective of research objects, most existing studies focus on major large-scale ports in China (Barros et al., 2016; Jiang et al., 2020; Yuen et al., 2013), Europe (Chang et al., 2018; Tovar & Wall, 2015), and along the Belt and Road or the Yangtze River (Song & Liu, 2020; Ye et al., 2020). However, there are few studies on the efficiency of regional port clusters.

The Yangtze River Delta and Pearl River Delta are two economic growth poles in China, playing an important role in the country's economic development. According to the 2019 China City Statistical Yearbook, the Yangtze River Delta and Pearl River Delta only account for 4.4% of China's administrative area. However, these two regions account for 12.8% of China's population, 29% of its GDP, 35.4% of its local fiscal revenue and 57.8% of its import and export trade volume. The two urban agglomerations have formed the Yangtze River Delta port cluster and the Pearl River Delta port cluster by their substantial economic capital, advanced technology, and excellent traffic network. The evolution of the two major port clusters represents the frontier and trend of China's port development. With continuous development of the two port clusters, they have some differences in their development direction, scale, and mode. A comparative study of port efficiency between the two will contribute to judging their development level and improving their operation status. Therefore, we use the meta Dynamic D.D.F. model to evaluate the efficiency performances of 23 major ports in the Yangtze River Delta and Pearl River Delta for 2010–2018.

The contributions of this study are as follows. First, this article estimates the port efficiency of the Yangtze River Delta and Pearl River Delta to study the efficiency mode of China's two major port systems. It supplements the research on port clusters and opens up directions for future research. Second, through the detailed analysis of input and output efficiencies, we can clearly understand the specific reasons for the inefficiency of different ports and formulate targeted improvement measures for the two port clusters. Third, this article uses the meta Dynamic D.D.F. model to avoid the regional differences and dynamic changes' influence on the efficiency measurement.

The remainder of this article is organised as follows. Section 2 reviews the relevant literature. Section 3 introduces the research method and data. Section 4 analyses the empirical results, and finally, Section 5 presents the conclusion.

2. Literature review

Port efficiency measures the effectiveness of resource allocation, reflecting the input–output capacity, competitiveness, and management level of ports (Pang, 2006). Studies on port efficiency can target two aspects: efficiency measurement and influencing factors.

Kim and Sachish (1986) used productivity indicators to evaluate port performance but they did not reflect port efficiency comprehensively. With the research development, numerous empirical studies used the D.E.A. model in port efficiency estimation. Roll and Hayuth (1993) first applied the D.E.A. method to estimate port efficiency of 20 international ports. Ablanedo-Rosas et al. (2010) adopted an output-oriented version of D.E.A. based on financial ratios to examine the relative efficiency of 11 major Chinese ports. Medal-Bartual et al. (2012) analysed the efficiency of Spanish ports using a non-radial D.E.A. model and found the efficiency of Spanish ports is highly efficient in the world. Zheng and Park (2016) used the D.E.A. model to compare the efficiency of major ports in South Korea and China, and the results showed that the efficiency of Korean ports is similar to that of the Chinese ports. Andrade et al. (2019) employed bi-objective multiple-criteria data envelopment analysis (BiO-M.C.D.E.A.) to estimate the efficiency of 20 Brazilian ports. Findings revealed that there are significant differences in port efficiency throughout the country. Zahran et al. (2020) proposed an imprecise D.E.A. model to estimate the efficiency of ports in the Arabian Peninsula. Mustafa et al. (2021) measured the efficiency of the Middle Eastern & South and East Asian ports through the D.E.A.-C.C.R. and D.E.A.-B.C.C. models, and only two ports in the Middle Eastern and South Asian and three ports in the East Asian were found efficient on both C.C.R. and B.C.C. models.

Stochastic frontier analysis and a combination of various methods were also extensively adopted. Wu and Goh (2010) studied emerging market ports and compared port efficiency in these markets with more developed markets via the D.E.A.-C.C.R., D.E.A.-B.C.C. and A&P models. Nguyen et al. (2016) compared the efficiency scores of Vietnamese ports in the standard D.E.A., S.F.A. and bootstrapped D.E.A. models and suggested the results of the bootstrapped D.E.A. is lower than those of the standard D.E.A. and S.F.A. Wei et al. (2019) used the D.E.A.-A.H.P. model and the principal component analysis method to evaluate the L.C.L. transshipment efficiency at port railway container intermodal terminal. Ye et al. (2020) combined the super-slacks-based measurement (S.B.M.) with Malmquist productivity index to measure the relative efficiency of 22 major ports along the Yangtze River from 2010 to 2016. Tsakiridis et al. (2021) used the S.F.A. and cluster analysis to assess the efficiency of Irish and North Atlantic Spanish ports. Findings indicated that the average technical efficiency of Irish ports is higher than that of Spanish ports.

While constantly creating economic value, ports also continuously produce environmental pollution that can affect their sustainable development. Thus, scholars have begun to consider environmental factors when measuring efficiency. They mainly estimated the environmental efficiency of ports in East Asia (Chang, 2013; Huang et al., 2019; Sun et al., 2017; Wang et al., 2020), India (Haralambides & Gujar, 2012), the U.S.A (Park et al., 2019) and Europe (Asgari et al., 2015; Quintano et al., 2020; Tichavska & Tovar, 2015). Furthermore, Lee et al. (2014) applied the S.B.M. model to estimate the environmental efficiency of emerging port cities, with results showing that New York, Kaohsiung, Busan, Rotterdam, Antwerp and Singapore are the most environmentally efficient cities, while Tianjin has the lowest environmental efficiency. Cheon et al. (2017) studied the relationship between economic efficiency and environmental efficiency of the top 10 U.S. seaports and found a positive correlation between them.

In addition to estimating the port efficiency in different countries, plenty of studies explored the influencing factors of port efficiency. Bichou (2013) used D.E.A. to measure the operational efficiency of 420 container terminals and analysed the impacts of operating and market conditions on container port efficiency. Oliveira and Cariou (2015) applied a truncated regression to examine how the degree of competition influences container port efficiency. They argued that fierce competition in ports reduces port efficiency. Using the S.F.A. model, Barros et al. (2016) found that the heterogeneity of Chinese ports affects port cost efficiency. Castellano et al. (2019) evaluated the impact of digital and communication technologies (D.C.T.) on port efficiency with the fuzzy D.E.A. approach. Findings pinpointed that D.C.T. solutions generally support port efficiency. Some studies attempted to explain the relationship between port efficiency and its ownership, concluding that management privatisation helps improve the efficiency of port operation (Lopez-Bermudez et al., 2019; Serebrisky et al., 2016; Wanke & Barros, 2016). Hynes et al. (2020) examined the effect of relative size on technical efficiency across the two port systems. Their work indicated a positive relationship between size and technical efficiency amongst ports in peripheral regions. Tovar and Wall (2022) studied the relationship between maritime connectivity and port efficiency in Spain and found a positive correlation between them.

The above studies pay attention to port efficiency and its influencing factors in a specific region but their research objects are too scattered to study the efficiency models of the regional port system as a whole. Moreover, their research also failed to account for regional differences and the dynamic changes in efficiency. In order to overcome the defects of previous studies, this article takes the port clusters of the Yangtze River Delta and Pearl River Delta as research objects, and studies the spatio-temporal characteristics and improvement space of port efficiency by using the meta dynamic D.D.F. model.

3. Methodology, variables and data

3.1. Meta Dynamic D.D.F. model

The D.E.A. is a linear programming model based upon Pareto's optimal solution for analysing the relative efficiency relationship between D.M.U.s. Charnes et al. (1978)

proposed the D.E.A.-C.C.R. model, which measures the performance of multiple inputs and outputs under constant returns to scale (C.R.S.). Banker et al. (1984) proposed the D.E.A.-B.C.C. model, amending the assumption of C.R.S. to variable returns to scale (V.R.S.). Tone (2001) proposed a S.B.M., in which the S.B.M. model based on slack variables corrects the defects in the radial efficiency measurement of C.C.R. and B.C.C. models, considers the slacks between input and output, and represents the efficiency by non-radial estimation. As the D.D.F. can handle both reduced input and increased output simultaneously, it has become a common tool for efficiency measurement. Chung et al. (1997) proposed the output-oriented distance function based on an extension of the radial output distance function (R.D.F.). The traditional D.D.F. employs a radial measurement mode, and it fails to cover all non-zero differences and all sources of inefficiency when calculating efficiency. Thus, the efficiency score is overestimated. In order to solve the above problem, Färe and Grosskopf (2010) and Chen et al. (2015) established the non-radial D.D.F. to provide more reasonable and accurate estimation results. The non-radial D.D.F. allows the inputs and outputs to be adjusted non-proportionally and it can identify all the slacks in input and output variables. Therefore, the non-radial D.D.F. is more general and flexible than the traditional D.D.F. in efficiency measurement (Zhou et al., 2012).

The traditional D.E.A. mainly focuses on static comparison but lacks estimation and analysis in different periods. In the development of dynamic D.E.A., Klopp (1985) proposed window analysis, which was first used for dynamic analysis, but he did not analyse the effect of carry-over activities between different periods. Färe and Grosskopf (1996) first put inter-connecting activities into the dynamic analysis. Following Färe and Grosskopf (1996), Tone and Tsutsui (2010) extended the model to a dynamic analysis with an S.B.M. At the same time, the traditional D.E.A. usually assumes that all producers have the same level of production technology when conducting efficiency estimations. However, the evaluated D.M.U.s often have different production technologies due to different geographical locations, national policies, social economy, etc. Therefore, Battese and Rao (2002), Battese et al. (2004) and O'Donnell et al. (2008) applied the concept of meta-frontier (M.F.) to the efficiency estimation. They gauged an M.F. through the use of overall samples, divided the D.M.U.s into groups, estimated the group frontier (G.F.) of each group separately, and finally used the distance between the M.F. and the G.F. to estimate whether the production technology level used by the group sample was close to the potential production technology level of the M.F.

This article is based on better evaluation performance of the non-radial D.D.F. However, the non-radial D.D.F. fails to consider the effect of intertemporal persistence. Thus, this article combines the dynamic D.E.A. of Tone and Tsutsui (2010) and the M.F. of O'Donnell et al. (2008) to propose the meta Dynamic D.D.F. model. Through an empirical study of this model, we measure port efficiencies in the Yangtze River Delta and Pearl River Delta and estimate the technical gaps between the ports in the two deltas.

The M.F. is an envelope curve for the G.F., and the ratio of the meta-frontier efficiency (M.F.E.) and group frontier efficiency (G.F.E.) is called the Technology Gap Ratio (T.G.R.):

$$TGR = \frac{MFE}{GFE} \quad (1)$$

We utilised Hu and Wang (2006) total-factor energy efficiency index to overcome any possible biases in the traditional efficiency indicators. The efficiency models are defined as:

$$Input\ \ efficiency = \frac{Targetinput}{Actualinput} \quad (2)$$

$$Desirable\ \ output\ \ efficiency = \frac{Actualdesirableoutput}{Targetdesirableoutput} \quad (3)$$

If the target inputs equal the actual inputs, then the efficiencies are 1, indicating overall efficiency; however, if the target inputs are less than the actual inputs, the efficiencies are less than 1, indicating overall inefficiency.

If the target desirable outputs are equal to the actual desirable outputs, the efficiencies are 1, indicating overall efficiency; however, if the target desirable outputs are more than the actual desirable outputs, the efficiencies are less than 1, indicating overall inefficiency.

3.2. Variables selection

This study takes 2010 to 2018 panel data from 14 ports in the Yangtze River Delta, including Shanghai, Ningbo-Zhoushan, Wenzhou, Taizhou-Z (Zhejiang Province), Nanjing, Suzhou, Taizhou-J (Jiangsu Province), Yangzhou, Nantong, Zhenjiang, Lianyungang, Changzhou, Hangzhou, Huzhou, and 9 ports in the Pearl River Delta including Guangzhou, Shenzhen, Dongguan, Zhuhai, Huizhou, Jiangmen, Zhaoqin, Zhongshan and Foshan. Data are collected from the China Statistical Yearbook, China Ports Yearbook, and statistical yearbooks of cities in the Yangtze River Delta and Pearl River Delta.

The selection of input and output variables of port efficiency should reflect the operation process and objectives of the port as much as possible. Table 1 summarises the input and output variables used in previous studies on port efficiency, in which nearly all selected studies have considered berth length as an input variable, while others used the number of berths (N.B.), terminal area and quantity of port production equipment. As piers and berths are important indicators of the port's production and service capacity (Song & Liu, 2020), this study selects pier length (P.L.) and the N.B. to reflect the port input.

Since sufficient and stable goods are the basic guarantees for efficient port production (Liao & Zhen, 2020), the output is measured by cargo throughput (C.T.) and container throughput (C) in most cases. We also employ the C.T. and C as output variables in this study. Considering that the port area (P.A.) directly determines the cargo quantity that a port can handle every year, we select the P.A. as the carry-over variable to reflect the role of land in the port efficiency.

Table 1. Input and output variables used in previous studies.

Authors	Research area	Research object	Input(s)	Output(s)
Cheon et al. (2009)	World's 98 container ports	Efficiency performance	Berth length, terminal area, and container crane	Container throughput
Chin and Low (2010)	East Asia	Environmental efficiency	Frequency of shipping services and bilateral trade flows	Capacity flows, NO_x, SO_2, CO_2, and particulate matter emissions
Hung et al. (2010)	Asia	Efficiency performance	Terminal area, ship-shore container gantry, the number of container berths, and terminal length	Container throughput
Bichou (2013)	World's 420 container ports	Efficiency performance	Terminal area, max draft, quay length, quay crane index, yard-stacking index, trucks and vehicles, and gates	Terminal throughput
Wanke (2013)	Brazil	Efficiency performance	The number of berths, warehousing area, and yard area	Solid bulk throughput and container throughput
Lee et al. (2014)	World's 11 container ports	Environmental efficiency	Labour population	Gross regional domestic product, container throughput, NO_x, SO_2, and CO_2 emissions
Oliveira and Cariou (2015)	World's 200 container ports	Efficiency performance	Berth length, gantry, yard cranes, and port and storage area	Container throughput
Tovar and Wall (2015)	Spain	Technical efficiency	Buildings and infrastructure, deposit surface area, labour, and intermediate consumption expenditure	Containerised merchandise, solid bulk, liquids, general non-container merchandise, and passengers
Beuren et al. (2018)	Brazil	Efficiency performance	Cargo capacity, quay length, and maximum draft	Cargo throughput and the number of shipping calls
Na et al. (2017)	China	Environmental efficiency	Berth length, port area, gantry cranes, and yard cranes	Container throughput and CO_2 emissions
Sun et al. (2017)	China	Environmental efficiency	Staff number and fixed assets	Operating cost, net profit, cargo throughput, and NO_x emissions
Chang et al. (2018)	Europe	Efficiency performance	Berth length, number of cranes, and terminal area	Cargo throughput
Castellano et al. (2019)	Italy	Efficiency performance	Investments, terminal area, and employees	Bulk liquid, bulk solid and container throughput

(*continued*)

Table 1. Continued.

Authors	Research area	Research object	Input(s)	Output(s)
Dong et al. (2019)	The 21st-Century Maritime Silk Road	Environmental and operational performance	The number of berths, quay cranes, and berth length	Container throughput and CO_2 emissions
Song and Liu (2020)	Yangtze River in China	Total factor productivity	The number of berths	Cargo throughput and container throughput
Ye et al. (2020)	Yangtze River in China	Efficiency performance	Quay-wall length, the number of berths, and channel depth	Cargo throughput and container throughput
Zahran et al. (2020)	Arabian Peninsula	Efficiency performance	The number of berths, equipment, and terminal storage area	Cargo throughput, number of vessels called, and container throughput
Huang et al. (2021)	The 21st-Century Maritime Silk Road	Efficiency performance	The number of berths, gantry cranes, and quay length	Container throughput

Source: Authors.

3.3. Data descriptions and analysis

Table 2 lists the basic statistics of all indicators and Figure 1 compares the input and output variables of ports in the two deltas. We see that the differences of various variables are significant, reflecting the variable heterogeneity of ports in the Yangtze River Delta and Pearl River Delta. P.L., the N.B., and C.T. in the Yangtze River Delta are significantly higher than those in the Pearl River Delta, but the C of ports in the latter is higher than that in the former. The P.L. of ports in the Yangtze River Delta fluctuates during 2010–2018, while the overall variable variation is smaller in the Pearl River Delta. The N.B. of ports in the two deltas shows a downward trend, as the decline in ports of the Yangtze River Delta is more significant than that in the Pearl River Delta. C.T. and C of ports in the two deltas increase significantly at similar rates.

A Kruskal-Wallis test is applied to further test the difference between the input and output variables of the Yangtze River Delta and Pearl River Delta. The p-value is compared with the confidence level α which is set as 0.1 to testify whether there is significant distinction between the average of the two regional groups. Table 3 provides the detailed test results. It shows that at a significant level of 10%, the P.L., C.T. and C of the Yangtze River Delta are significantly different from those of the Pearl River Delta in 2010–2018. But the N.B. and P.A. of the Yangtze River Delta are not significantly different from those of the Pearl River Delta in 2010–2018.

Overall, there are still differences in P.L., C.T. and C in the two different deltas.

4. Empirical results

4.1. Overall port efficiency score

Table 4 shows the efficiency score of each port, and Figure 2 compares the average efficiency score of ports in the Yangtze River Delta and Pearl River Delta from 2010

Table 2. Descriptive statistics of variables.

Variables	Mean	Minimum	Maximum	Std. dev.
Pier length (m)	33,703.86	3,124.00	224,386.00	40,047.50
The number of berths (units)	431.73	40.00	3,222.00	593.47
Cargo throughput (10,000 tons)	20,718.10	1,597.00	108,439.00	21,909.46
Container throughput (10,000 TEUs)	526.42	0.22	4,201.00	923.68
The port area (m^2)	2,904,617.25	80,657.00	9,354,851.00	2,899,729.02

Source: Authors.

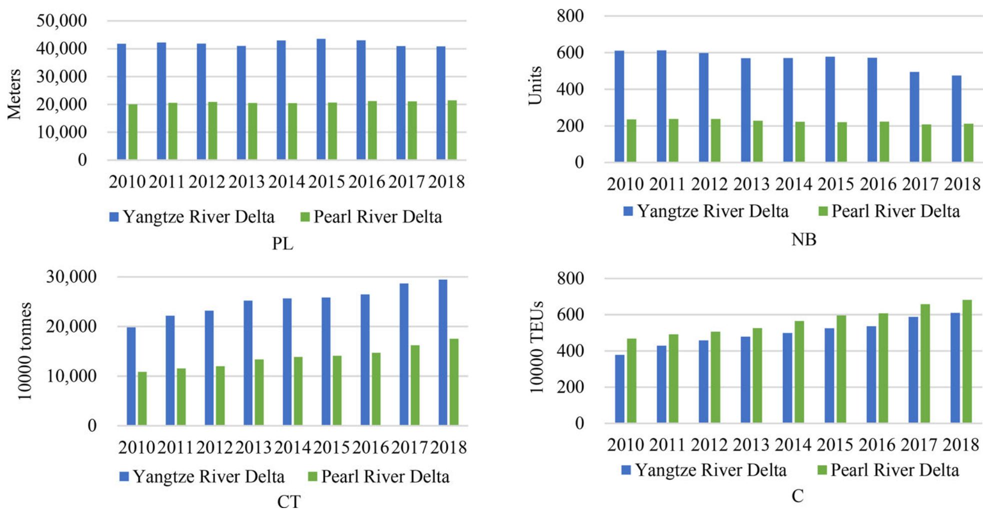

Figure 1. Input–output variables of ports in the Yangtze River Delta and Pearl River Delta from 2010 to 2018.
Source: Authors.

Table 3. A Kruskal-Wallis test between the Yangtze River Delta and Pearl River Delta in 2010–2018.

Variables	Average of the Yangtze River Delta	Average of the Pearl River Delta	Kruskal-Wallis Test
Pier length	42020.94	20766.19	0.05*
The number of berths	564.50	225.21	0.10
Cargo throughput	25166.98	13797.62	0.04**
Container throughput	500.41	566.88	0.08*
The port area	3185747.06	2467304.21	0.20

Notes
*On behalf of the two-tailed test, the confidence interval 0.1 is significant.
**On behalf of the two-tailed test, the confidence interval 0.05 is significant.
Source: Authors.

to 2018. Shanghai, Taizhou-Z, Taizhou-J, Shenzhen and Zhongshan ports score 1 in overall efficiency. Several studies have found that port efficiency increases significantly with port size (Pérez et al., 2020; Ye et al., 2020). Large ports such as Shanghai and Shenzhen have the advantages of specialisation and economies of scale. They can attract significant dedicated investments to solve congestion or other inefficiencies that might characterise the majority of other ports (Hilda & Alessio, 2021). Although the input and output quantities of Zhongshan are small, it does achieve relatively high efficiency, indicating that regardless of port scale, a port should plan its facility

Table 4. The overall efficiency scores of 23 ports in the Yangtze River Delta and Pearl River Delta from 2010 to 2018.

DMU	2010	2011	2012	2013	2014	2015	2016	2017	2018	Mean
Shanghai	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Ningbo-Zhoushan	0.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.748	0.968
Wenzhou	0.378	0.401	0.364	0.330	0.332	0.392	0.437	0.462	0.211	0.364
Taizhou-Z	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Nanjing	0.482	0.565	0.639	0.534	0.592	0.621	0.707	0.725	0.449	0.585
Suzhou	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.732	0.966
Taizhou-J	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Yangzhou	0.268	0.306	0.351	0.310	0.410	0.462	0.448	0.414	0.202	0.347
Nantong	1.000	1.000	0.539	1.000	1.000	1.000	1.000	1.000	1.000	0.936
Zhenjiang	0.949	1.000	0.506	0.528	0.484	0.361	0.388	0.483	0.377	0.536
Lianyungang	0.806	0.992	0.755	0.851	1.000	1.000	1.000	1.000	1.000	0.929
Changzhou	0.342	0.373	0.283	0.259	0.203	0.228	0.261	0.260	0.098	0.252
Hangzhou	0.213	0.225	0.212	0.201	0.257	0.285	0.258	0.422	0.166	0.245
Huzhou	0.270	0.344	0.360	0.236	0.109	0.097	0.131	0.190	0.119	0.199
Guangzhou	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.622	0.949
Shenzhen	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Dongguan	0.192	0.236	0.323	0.422	0.492	0.488	0.565	0.632	0.438	0.407
Zhuhai	0.497	0.560	0.543	0.897	0.453	0.493	0.557	0.627	0.403	0.549
Huizhou	0.667	0.706	0.755	1.000	0.653	0.884	0.693	0.583	0.530	0.709
Jiangmen	0.303	0.378	0.392	0.328	0.321	0.378	0.442	0.434	0.210	0.351
Zhaoqin	0.115	0.200	0.245	0.215	0.252	0.295	0.566	1.000	0.433	0.331
Zhongshan	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Foshan	0.346	0.329	0.253	0.232	0.275	0.322	0.380	0.426	0.326	0.319

Source: Authors.

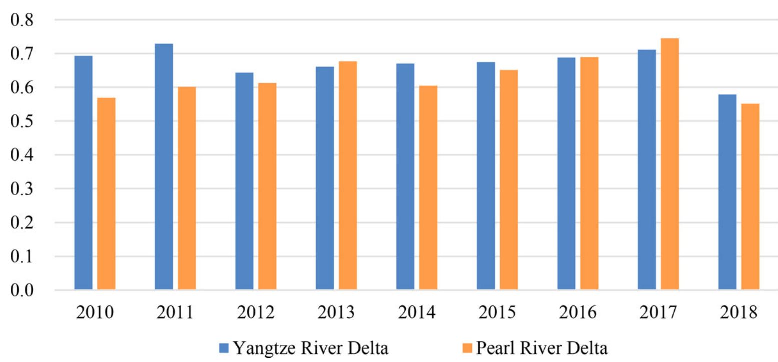

Figure 2. Port efficiency in the Yangtze River Delta and Pearl River Delta from 2010 to 2018.
Source: Authors.

input and allocate its resource elements according to actual demand so as to achieve excellent operational efficiency (Cheon, 2008). About 80% of the ports are inefficient, so there is some leeway for their efficiency improvements. The port efficiencies of Ningbo-Zhoushan, Suzhou, Nantong, Lianyungang, and Guangzhou are above 0.8 but not as high as 1. Five ports have an efficiency score between 0.4 and 0.8. Eight ports, including Wenzhou, Yangzhou, Changzhou, Hangzhou, Huzhou, Jiangmen, Zhaoqin and Foshan, have an average efficiency score below 0.4, while Huzhou has the lowest efficiency of 0.199. The results confirm that location plays a role in facilitating higher efficiency scores (Barros et al., 2016). Because most inefficient ports are dry ports, which have low trade frequency compared with coastal ports, making them challenging to form economies of scale.

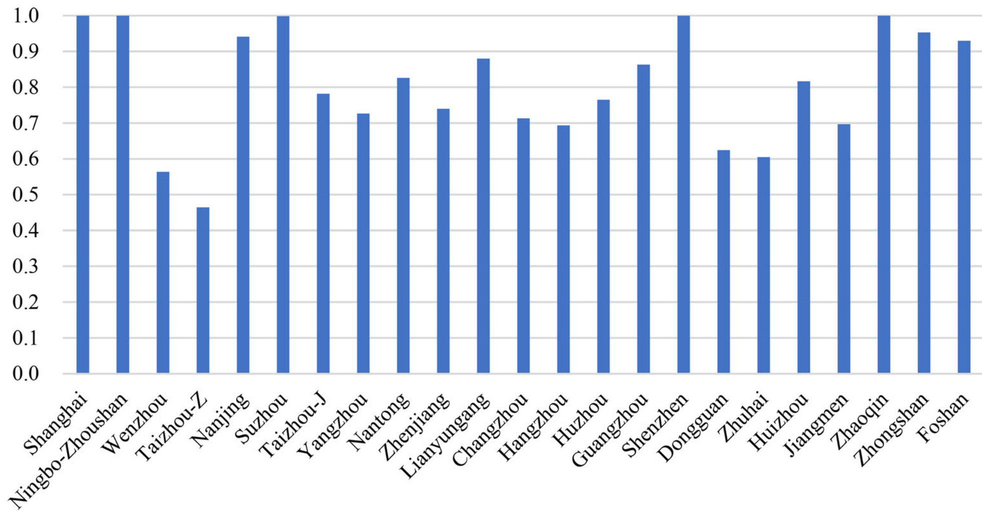

Figure 3. Efficiency gap for each port.
Source: Authors.

From analysis on the time change, the port efficiencies of Zhenjiang, Changzhou and Huzhou show a downward trend from 2010 to 2018, while the port efficiency of Lianyungang shows an upward trend. Overall, the efficiency improvement of Zhaoqin port in the Pearl River Delta is the most significant, as the efficiency score increases by 0.318 in 2018 compared with 2010. The efficiency of Zhenjiang port fluctuates greatly with the most obvious drop between 2010 and 2018.

Comparing the efficiency of ports in the Yangtze River Delta and Pearl River Delta from 2010 to 2018, we find that the average port efficiency in the Yangtze River Delta is higher than that in the Pearl River Delta. The proportion of high-efficiency ports in the Yangtze River Delta is relatively higher. Seven ports (one-half) in the Yangtze River Delta have an average efficiency above 0.8, while ports with efficiency above 0.8 in the Pearl River Delta account for only one-third. However, the proportion of inefficient ports in the Yangtze River Delta is also higher, indicating that port development in the Yangtze River Delta is more unbalanced than in the Pearl River Delta. The imbalance is caused by disparities in channel conditions, hinterland economies, consolidation and distribution systems, and government policies along the Yangtze River (Ye et al., 2020). The efficiency gap between the two clusters gradually falls in recent years, indicating that the Yangtze River Delta's port operations are better than that of the Pearl River Delta. Still, the development advantages of ports in the Yangtze River Delta decrease over time.

4.2. Technology gap score based on the M.F

Figure 3 gives the technology gap of each port, and Figure 4 shows the change in the trend of the technology gap of ports in the Yangtze River Delta and Pearl River Delta from 2010 to 2018. The technology gap only considers three significant variables: P.L., C.T., and C. From Figure 3, Shanghai and Ningbo-Zhoushan ports in the Yangtze River Delta have an average T.G.R. of 1, while Shenzhen and Zhaoqin ports

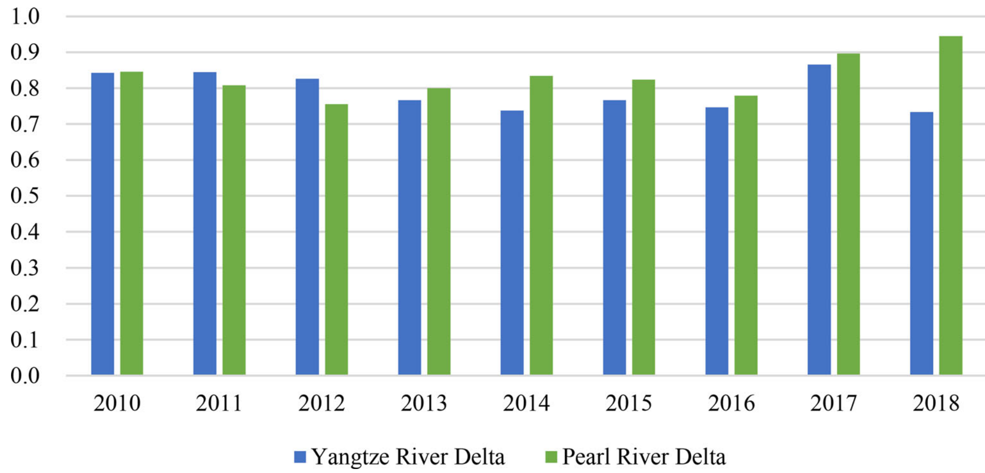

Figure 4. Efficiency gap comparison from 2010 to 2018.
Source: Authors.

in the Pearl River Delta also have a T.G.R. of 1, indicating these ports have reached the potential best technology level. The average T.G.R. of Wenzhou and Taizhou-Z ports are below 0.6, indicating they are far from the potential best technology level. Figure 4 proposes a difference between the Yangtze River Delta and Pearl River Delta in the technology gap. The average T.G.R. of ports in the Yangtze River Delta and Pearl River Delta are 0.792 and 0.832. Therefore, there is a gap between the actual technical level and the potential best technical level in the two port clusters, with 20.8% and 16.8% room for improvement, respectively. Between 2011 and 2012, the T.G.R. of ports in the Yangtze River Delta is higher than that in the Pearl River Delta. After 2012, the average technology gap of ports in the Pearl River Delta exceeds that in the Yangtze River Delta.

Table 5 illustrates the efficiency rankings of each port under the M.F. and G.F. from 2010 to 2018. No gap between the M.F. and G.F. rankings appears for Shanghai, Ningbo-Zhoushan and Shenzhen ports. However, the efficiency ranking of most ports in all ports differs from the efficiency ranking in each region. For example, both Taizhou-Z and Guangzhou rank 1st in 2018 regionally, but 21st and 8th, respectively, compared to ports in the two deltas, indicating that some ports are efficient in their region, but there is still room for improvement compared with other regions. Furthermore, the difference between the M.F. and G.F. rankings of Wenzhou and Taizhou-Z ports shows an increasing trend, while the gaps of other ports change little.

4.3. Efficiency scores of input and output variables

Tables 6 and 7 provide the efficiency scores for P.L., the N.B., C.T., and C for each port from 2010 to 2018. We note that all input and output variables of Shanghai, Taizhou-Z, Taizhou-J, Shenzhen and Zhongshan ports have efficiency scores of 1 for the nine years. Ningbo-Zhoushan, Suzhou, Nantong, Zhenjiang, Lianyungang,

Table 5. Comparison of the M.F. and G.F. port rankings from 2010 to 2018.

	2010		2011		2012		2013		2014		2015		2016		2017		2018	
DMU	MF	GF	MF	GF	MF	GF	MF	GF	MF	GF	MF	GF	MF	GF	MF	GF	MF	GF
Shanghai	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Ningbo-Zhoushan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Wenzhou	15	14	15	15	15	15	15	13	15	13	15	13	17	14	17	11	20	11
Taizhou-Z	9	8	9	8	9	7	10	1	10	8	10	7	14	1	16	1	21	1
Nanjing	20	20	20	20	20	20	20	20	20	20	20	21	16	19	11	15	11	13
Suzhou	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	9
Taizhou-J	10	11	12	12	12	12	9	9	18	19	19	19	12	15	10	13	10	12
Yangzhou	19	19	19	19	19	19	19	18	19	18	17	15	20	20	21	21	17	18
Nantong	12	13	13	14	13	14	11	15	11	14	13	14	9	10	8	9	6	1
Zhenjiang	17	17	16	17	17	17	14	14	14	15	18	18	18	17	15	17	14	15
Lianyungang	7	1	6	7	7	10	6	8	7	1	7	8	7	1	1	1	7	1
Changzhou	21	21	21	21	21	21	22	22	22	22	22	22	22	22	22	22	22	21
Hangzhou	22	22	23	22	23	22	21	21	21	21	21	20	21	21	20	18	18	17
Huzhou	23	23	22	23	22	23	23	23	23	23	23	23	23	23	23	23	23	23
Guangzhou	6	1	7	1	6	1	7	1	6	1	6	1	6	1	1	1	8	1
Shenzhen	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Dongguan	14	12	14	11	14	9	12	11	12	9	12	9	11	12	12	12	12	14
Zhuhai	11	10	10	10	10	8	16	12	13	10	14	10	13	13	13	14	13	16
Huizhou	8	9	8	9	8	11	8	10	9	11	9	11	10	11	14	16	16	20
Jiangmen	18	15	17	13	16	13	18	16	16	16	16	16	19	18	19	20	19	22
Zhaoqin	13	16	11	16	11	16	13	17	8	12	8	12	1	1	1	1	9	10
Zhongshan	1	1	1	1	1	1	1	1	1	1	1	1	8	9	9	10	1	1
Foshan	16	18	18	18	18	18	17	19	16	16	11	17	15	16	18	19	15	19

Source: Authors.

Guangzhou, Huizhou and Zhaoqin ports have an efficiency of 1 in some years and room for improvement in other years.

The P.L. efficiency scores of different ports vary widely. There is no need for improvement in Shanghai, Taizhou-Z and Taizhou-J ports in the Yangtze River Delta and Shenzhen and Zhongshan ports in the Pearl River Delta. However, ports with a P.L. efficiency score below 0.6 include Changzhou, Hangzhou, Huzhou and Foshan. The input inefficiency of these ports means they do not efficiently use the input factors (Na et al., 2017). Their P.L. does not match the actual demands, and further rational planning of P.L. is needed.

The N.B. is a key aspect for increasing the overall productivity performance (Hilda & Alessio, 2021). Ports whose N.B. shows a nine-year efficiency score of 1 are Shanghai, Taizhou-Z, Taizhou-J, Shenzhen and Zhongshan. The N.B. in Ningbo-Zhoushan, Suzhou, Guangzhou and Nantong ports has also reached an effective level in most years. The utilisation ratio of berths is relatively high in the above ports. There are five ports with an average efficiency below 0.4. These ports are small in scale, and fierce homogeneous competition has caused structural overcapacity (Ye et al., 2020). Such ports can promote transformation and upgrading by optimising their structure.

From the perspective of change in trend, the P.L. efficiency of most ports shows an upward trend except for Zhenjiang, Changzhou, Huzhou, Zhuhai and Huizhou. The N.B. efficiency of most ports in the Yangtze River Delta and Pearl River Delta has shown a downward trend in recent years, indicating that excessive construction of berths has led to the decline of port efficiency.

Table 6. Efficiency scores for P.L. and the N.B. from 2010 to 2018.

	2010		2011		2012		2013		2014		2015		2016		2017		2018	
DMU	PL	NB	PL	NB	PL	NB	PL	NB	PL	NB	PL	NB	PL	NB	PL	NB	PL	NB
Shanghai	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Ningbo-Zhoushan	0.999	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.599	0.856
Wenzhou	0.549	0.271	0.573	0.350	0.533	0.285	0.496	0.400	0.498	0.498	0.563	0.563	0.609	0.402	0.632	0.382	0.348	0.308
Taizhou-Z	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Nanjing	0.650	0.498	0.722	0.722	0.780	0.663	0.696	0.696	0.744	0.744	0.766	0.766	0.829	0.723	0.840	0.703	0.479	0.620
Suzhou	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.846	0.846
Taizhou-J	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Yangzhou	0.422	0.246	0.469	0.338	0.520	0.288	0.473	0.330	0.581	0.581	0.632	0.595	0.619	0.389	0.586	0.400	0.336	0.336
Nantong	1.000	1.000	1.000	1.000	0.617	0.701	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Zhenjiang	0.959	0.974	1.000	1.000	0.672	0.447	0.692	0.692	0.652	0.652	0.530	0.530	0.559	0.489	0.651	0.532	0.548	0.548
Lianyungang	0.803	0.893	0.944	0.996	0.724	0.861	0.793	0.919	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Changzhou	0.510	0.226	0.543	0.404	0.441	0.211	0.411	0.237	0.338	0.281	0.371	0.279	0.414	0.157	0.413	0.156	0.179	0.131
Hangzhou	0.351	0.101	0.368	0.187	0.350	0.098	0.335	0.131	0.409	0.272	0.444	0.254	0.411	0.117	0.593	0.144	0.285	0.120
Huzhou	0.426	0.151	0.512	0.452	0.529	0.215	0.382	0.197	0.197	0.139	0.177	0.115	0.231	0.103	0.320	0.105	0.213	0.105
Guangzhou	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.767	0.649
Shenzhen	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Dongguan	0.322	0.147	0.382	0.282	0.488	0.374	0.594	0.594	0.660	0.660	0.656	0.656	0.722	0.527	0.774	0.774	0.609	0.609
Zhuhai	0.664	0.572	0.718	0.718	0.704	0.585	0.945	0.946	0.623	0.623	0.661	0.661	0.715	0.703	0.771	0.667	0.453	0.574
Huizhou	0.800	0.800	0.816	0.828	0.782	0.861	0.710	1.000	0.790	0.790	0.810	0.938	0.781	0.819	0.712	0.737	0.543	0.693
Jiangmen	0.465	0.250	0.549	0.523	0.563	0.288	0.495	0.439	0.486	0.469	0.548	0.485	0.613	0.540	0.606	0.346	0.347	0.324
Zhaoqin	0.207	0.150	0.334	0.334	0.394	0.308	0.354	0.354	0.402	0.394	0.456	0.456	0.723	0.360	1.000	1.000	0.605	0.421
Zhongshan	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Foshan	0.514	0.489	0.495	0.397	0.404	0.266	0.377	0.274	0.431	0.306	0.487	0.300	0.551	0.303	0.597	0.330	0.492	0.248

Source: Authors.

Table 7. Efficiency scores for C.T. and C from 2010 to 2018.

	2010		2011		2012		2013		2014		2015		2016		2017		2018	
DMU	CT	C	CT	C	CT	C	CT	C	CT	C	CT	C	CT	C	CT	C	CT	C
Shanghai	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Ningbo-Zhoushan	0.999	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.874	0.874
Wenzhou	0.689	0.689	0.701	0.701	0.682	0.682	0.665	0.665	0.666	0.427	0.696	0.339	0.719	0.719	0.731	0.731	0.605	0.354
Taizhou-Z	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1. 000	1.000
Nanjing	0.741	0.741	0.783	0.783	0.819	0.819	0.767	0.767	0.796	0.796	0.811	0.811	0.854	0.854	0.862	0.862	0.725	0.725
Suzhou	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.866	0.766
Taizhou-J	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Yangzhou	0.634	0.634	0.653	0.653	0.676	0.634	0.655	0.655	0.705	0.226	0.731	0.258	0.724	0.724	0.707	0.707	0.601	0.209
Nantong	1.000	1.000	1.000	1.000	0.770	0.370	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Zhenjiang	0.975	0.975	1.000	1.000	0.753	0.322	0.764	0.376	0.742	0.290	0.680	0.238	0.694	0.326	0.742	0.354	0.689	0.181
Lianyungang	0.903	0.903	0.996	0.996	0.878	0.878	0.925	0.925	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Changzhou	0.671	0.665	0.686	0.079	0.642	0.642	0.629	0.502	0.602	0.072	0.614	0.082	0.631	0.631	0.630	0.630	0.549	0.134
Hangzhou	0.607	0.009	0.613	0.001	0.606	0.007	0.600	0.006	0.628	0.003	0.643	0.075	0.629	0.031	0.711	0.127	0.583	0.023
Huzhou	0.635	0.021	0.672	0.002	0.680	0.076	0.618	0.111	0.555	0.059	0.548	0.098	0.565	0.203	0.595	0.480	0.560	0.174
Guangzhou	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.811	0.811
Shenzhen	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Dongguan	0.596	0.596	0.618	0.524	0.661	0.661	0.711	0.711	0.746	0.746	0.744	0.744	0.783	0.783	0.816	0.816	0.719	0.719
Zhuhai	0.749	0.749	0.780	0.780	0.772	0.772	0.948	0.948	0.726	0.726	0.747	0.747	0.778	0.778	0.814	0.814	0.701	0.701
Huizhou	0.833	0.833	0.853	0.853	0.878	0.878	1.000	0.833	0.827	0.766	0.942	0.942	0.847	0.847	0.792	0.687	0.765	0.503
Jiangmen	0.652	0.652	0.689	0.497	0.696	0.696	0.664	0.664	0.661	0.624	0.689	0.583	0.721	0.721	0.717	0.717	0.605	0.605
Zhaoqin	0.558	0.558	0.600	0.600	0.623	0.623	0.607	0.607	0.626	0.626	0.648	0.648	0.783	0.783	1.000	1.000	0.717	0.717
Zhongshan	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Foshan	0.634	0.673	0.664	0.664	0.627	0.627	0.616	0.616	0.637	0.637	0.661	0.661	0.690	0.690	0.713	0.713	0.663	0.663

Source: Authors.

The N.B. efficiency of most ports is lower than that of the P.L. For example, the average N.B. efficiency of Wenzhou, Nanjing, Yangzhou, Changzhou, Huzhou, Dongguan, Zhuhai, Jiangmen, Zhaoqin and Foshan ports is lower than that of the P.L. The average input efficiency of the Pearl River Delta ports (0.701) is lower than that of the Yangtze River Delta ports (0.714), especially in the P.L. efficiency. Therefore, ports in the Yangtze River Delta and Pearl River Delta should conduct reasonable port berth construction, while ports in the Pearl River Delta also need to optimise the input of P.L.

The average C.T. efficiency of the two port clusters is above 0.6, and 11 ports have C.T. efficiency exceeding 0.8. The average C.T. efficiency score of ports in the Yangtze River Delta is 0.836, slightly higher than that in the Pearl River Delta at 0.816. Therefore, the cargo handling efficiency of the two port clusters is high, and ports in the Yangtze River Delta perform better.

The C efficiency of seven ports in the Yangtze River Delta and three ports in the Pearl River Delta has reached 1. C efficiencies of Changzhou, Hangzhou, and Huzhou ports in the Yangtze River Delta are below 0.4. Especially for Hangzhou port, the C efficiency score is only 0.1 in 2017. The C efficiency of all ports in the Pearl River Delta is above 0.6, and the average efficiency reaches 0.804. The average C efficiency of ports in the Yangtze River Delta (0.697) is lower than that in the Pearl River Delta, indicating that the C efficiency of the Yangtze River Delta needs further improvement. This is due to the unbalanced development of container ports in the Yangtze River Delta, resulting in the containerisation construction of small and medium-sized ports subject to large ports (Chen et al., 2019). Ports in the Yangtze River Delta can enhance their container transportation capacity by strengthening the infrastructure construction of their container yards and terminals to improve port operational efficiency.

5. Conclusion

The objects of former research are too dispersed and independent, thereby preventing an examination of the efficiency pattern of regional port systems from the perspective of geography (Jiang et al., 2017). This study is one of the few literatures on port efficiency from the perspective of port clusters. We estimate and analyse the port efficiency, P.L., the N.B., C.T., and C efficiencies in the Yangtze River Delta and Pearl River Delta, thus clarifying the efficiency pattern of the two most important port clusters in China. Findings reveal that most ports are inefficient, and the internal efficiency difference of the Yangtze River Delta port cluster is more significant. The average efficiency of the Yangtze River Delta port cluster is higher than that of the Pearl River Delta port cluster, coinciding with the finding of Li et al. (2013). However, the T.G.R. of ports in the Pearl River Delta gradually exceeds that in the Yangtze River Delta. In addition, different from other literatures, this study explores the path of port efficiency improvement through sub-item efficiency evaluation. From the input efficiency perspective, the N.B. efficiency is lower than the P.L. efficiency. The two port clusters should optimise the investment in port infrastructure and reduce blind competition. From the output efficiency, the C.T. efficiency of the two port clusters is high, but the C efficiency of the Yangtze River Delta port cluster needs further improvement.

Our research can provide helpful information and enlightenment for the government and port enterprises, which is conducive to promoting the development of port clusters and urban agglomerations in the Yangtze River Delta and Pearl River Delta. Based on our findings, we recommend that the Chinese government should strengthen joint port construction and regional cooperation, promote the integration and complementarity of port resources, and form a cluster effect. Large ports such as Shanghai and Shenzhen should play a role in radiating and driving the development of their surrounding ports. Wenzhou, Zhongshan and other small ports need to strengthen their professional positioning and avoid cutthroat competition with other ports. The Yangtze River Delta port cluster should improve its container transportation service ability. The Pearl River Delta port cluster should optimise the berth and wharf construction to match the actual demand. Port enterprises can continue to improve the port management mode, strengthen the planning and construction, and promote the intensive utilisation of resources. Finally, goals can target enhancing the information construction of ports and strengthening the core technology and service capabilities to improve the port operational efficiency.

This study analyses the efficiency of the Yangtze River Delta port cluster and Pearl River Delta port cluster and the internal reasons for the inefficiency, which can provide a reasonable decision-making basis for the two port clusters. Moreover, this research can be a reference for the construction of world port clusters. However, there are certain limitations to our study. Our efficiency evaluation does not include labour and technology factors due to the unavailability of data. Future research should consider labour force and technology when calculating port efficiency to make the index system more comprehensive. We also mainly discuss the impact of internal factors on port efficiency. Therefore, future studies should consider various external factors affecting port efficiency. Finally, this study only analyses the efficiency of port clusters in China, and the results may not apply to all port clusters in the world.

Disclosure statement

No potential conflict of interest was reported by the authors.

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