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Efficiency Pattern and Spatial Strategy of Ports in Yangtze River Delta Region

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Abstract: This paper measures the efficiency of ports in the Yangtze River Delta Region (YRDR) in 2008 and 2013 using port berth quantity, quay length, and human resources as input indicators, using cargo and container throughput as output indicators, and considering traditional (foreign trade dependence and industrialization level) and modern environmental factors (traffic line density, financial development level, and informatization level). To achieve such aim, this study constructs a multi-stage data envelopment analysis model (DEA) that identifies effective port decision-making units (DMUs) and generates a highly accurate conclusion by eliminating the interference from the exogenous environment and random errors. First, the external environment significantly affects port efficiency, with the traditional environmental factors showing huge fluctuations and the modern environmental factors producing great benefits. Second, the efficiency of ports in YRDR has increased from 2008 to 2013 primarily because of their pure technical efficiency. Third, the weighted standard deviation ellipse (SDE) analysis results reveal that the efficiency pattern of ports significantly deviates from their throughput pattern, while the center of SDE of port efficiency moves from the eastern coastal regions to the northwest regions. Based on these findings, this paper proposes spatial development strategies for YRDR, such as creating an unblocked environment where spatial elements can freely circulate, intensifying port-city joint development, implementing differentiated policies, and focusing on the spatial collaboration of port efficiency.

Keywords: Yangtze River Delta Region (YRDR); port efficiency; data envelopment analysis (DEA) model; stochastic frontier analysis (SFA); super efficiency analysis

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1 Introduction

Apart from acting as basic supporting units of the comprehensive transportation system of China, ports also serve as important bases for promoting the 'One Belt, One Road' strategy and the development of the Yangtze River Economic Belt. Studies and practices in the 21st century have underscored the importance of adapting port management to the integrated development of the global trade supply chain. Accordingly, port efficiency has become a key factor that affects global trade (Laurence, 2015). With the advancement of the international division of labor and the significant developments in economic globalization, improving port efficiency has increasingly become an important task that can result in a dynamic increase of comparative advantages (Zhang and Deng, 2013). Under the influence of external environments, including globalization, informatization, new free trade agreements, and domestic economic norms, traditional ports no longer depend on transit loading. Modern ports have shifted from traditional epitaxial growth to internal driving growth while focusing on

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functional upgrades, structural optimization, and efficiency improvements. The efficiency level of a port greatly reflects the international competitiveness of a country (Jose, 1995).

Port efficiency and its assessment have always been mainstream topics in western port geography research over the past century (Pan and Cao, 2014). These studies have adopted production frontier and non-production frontier methods. The non-production frontier method often analyzes the local efficiency of a single element (De, 1987; César and Olaf, 2013) or creates multiple indicators (Jose, 1995; Ricardo *et al*., 2003; Dong, 2012). However, the findings tend to be superficial and inappropriate for measuring port efficiency, which is a multi-input and multi-output production process. The production frontier method can be further divided into parametric and nonparametric methods. The parametric methods include stochastic frontier analysis, thick frontier analysis, and distribution free approach, while nonparametric methods mainly include data envelopment analysis (DEA) and free disposal hull. DEA has been widely applied because this method does not require the definition of production functions and does not impose strict requirements on indexes. Since its introduction by Roll and Hayuth in port efficiency research (Roll and Hayuth, 1993), DEA has been widely applied in assessing port efficiency. Many amendments to the DEA approach have also been proposed since the 21st century. For example, the Slack Based Model (SBM) has been proposed to address the radial and angle defects of the traditional DEA model (Anthony and Joyce, 2010). The Tobit model has been applied to eliminate the influence from environmental factors (Hugh *et al*., 2004). The DEA model and super-efficiency DEA model have been proposed to identify effective decision-making units (DMUs; Barros, 2006), and the bootstrap DEA approach has been proposed to increase the robustness of these models (Hung *et al*., 2010).

Although many studies on port efficiency have been published in China, only few have investigated port efficiency from the perspective of geography, albeit not profoundly enough. Ren and Yang (1998) emphasized the urgent need to improve the efficiency of container ports in China. Wang and César (2011) argued that the inland distribution network improved the operational efficiency of ports, especially hub ports. Yang and Pan (2011) considered port efficiency an important parameter for the system structures of port cities during the process of constructing the port-city system dynamics model. Cheng and Wang (2015) argued that introducing foreign investments could efficiently address the lack of capital for constructing ports and improving port management efficiency. Some scholars have studied the operational efficiency of ports from the perspective of provincial territory. For example, Peng (2012) and Wang *et al.* (2010) studied the ports in Zhejiang Province, and found that the efficiency potential of these ports was not maximized and that business outsourcing would effectively improve the production and management efficiency of port organizations. Li *et al.* (2012) launched a collaborative development research on the logistic efficiency and hinterland economy of ports in Liaoning Province using the DEA model, and argued that the improvement of port logistic efficiency should not only depend on technical progress but also consider regional differences. Nevertheless, the problems relating to the distribution of port efficiency, the rationale behind the formation of an efficiency pattern, and the similarities and differences between efficiency and traditional cargo volume must be addressed theoretically and practically.

In sum, despite fruitful advancements in port efficiency research, some aspects of this topic remain unaddressed. First, local and foreign studies have focused on seaport efficiency, but only few have investigated the efficiency of inland ports. Second, the influence of environmental factors and random errors has not been eliminated in the research process and the sequence of effective port DMUs has not been considered. Third, the objects of research are too disperse and independent, thereby preventing an examination of the efficiency pattern of regional port system from the perspective of geography. To address these gaps, this paper evaluates the efficiency of the major ports in the Yangtze River Delta Region (YRDR) from the perspective of the port system by using the multi-stage DEA model, integrating the parametric and nonparametric methods, and considering the influence of exogenous environment and random interference factors on port efficiency.

2 Materials and Methods

2.1 Profile of research area

The YRDR is a port agglomeration with the densest port distribution and highest throughput in China (Fig. 1). In 2014, the cargo, container, and foreign trade throughputs of the primary ports in YRDR account for 32.6%, 35.8%, and 33.8%, of the total port throughputs in the country, respectively. Therefore, YRDR has a vital role in the regional economic development and the reform and opening up of China. As the center of the global shipping market rapidly shifts toward the Asia-Pacific, the resource allocation and efficiency of ports must be greatly improved to develop the port system of YRDR under the new circumstances. Therefore, measuring the efficiency and spatial pattern of the port system in this area and determining a direction for improvement can both offer theoretical and practical significance.

2.2 Research methods

This paper adopts a four-stage DEA model to measure the operation efficiency of the primary ports in YRDR. These stages are described as follows:

Stage one: Traditional DEA model. Given that the input factors can be controlled much easier than the output factors, this paper adopts an input-oriented variable return to scale model (VRS) with a changeable scale return. Given its maturity, the rationale and mathematical formula of this model are not elaborated in this paper.

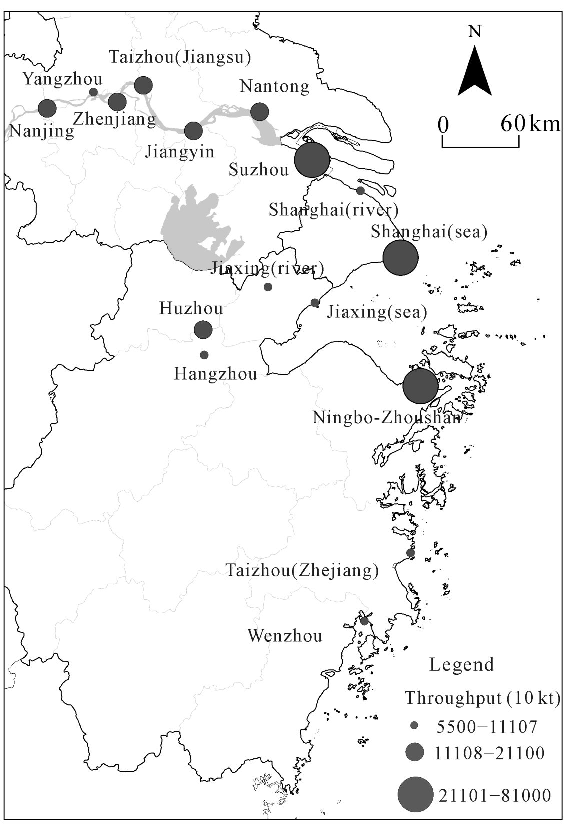

Fig. 1 Spatial pattern of main ports in the Yangtze River Delta Region

Stage two: SFA analysis model. According to Fried *et al*. (2002) the slack variables that are calculated in stage one are co-affected by management inefficiency, environmental factors, and statistical noise. Given its ability to distinguish the effects from environmental factors and random errors, the SFA analysis model can establish the following regression equation that covers slack variables, environmental factors, random factors, and management inefficiency items:

$$S_{ni} = f(Z_i;\beta_n) + \nu_{ni} + \mu_{ni} \quad i = 1,2,...,I; n = 1,2,...,N$$

where S_{ni} is the slack value of the nth input of the ith DMU; Z_i is an environmental variable of the ith DMU; β_n is the coefficient of the environmental variable; $\nu_{ni}+\mu_{ni}$ are mixed errors; ν_{ni} represents the stochastic disturbance that follows the $\nu - N(0, \sigma_\nu^2)$ distribution , μ_{ni} is the management inefficiency that follows normal distributions in zero truncation, that is, $\mu_{ni} - N^+(\mu, \sigma_\mu^2)$, and ν_{ni} and μ_{ni} are independent and irrelevant. If $\gamma = \sigma_\mu^2/(\sigma_\mu^2+\sigma_\nu^2)$ approaches 1, then the influence of management factors plays a dominant role. However, if $\gamma = \sigma_\mu^2/(\sigma_\mu^2+\sigma_\nu^2)$ approaches 0, then the random errors play a dominant role.

The regression results of the SFA analysis model are used to adjust the inputs of the original DMU, adjust all DMUs to identical environmental conditions, and consider the influence of stochastic disturbances.

$$X^*_{ni} = X_{ni} + [\max(f(Z_i;\widehat{\beta}_n)) - f(Z_i;\widehat{\beta}_n)] + [\max(\nu_{ni}) - \nu_{ni}] \quad i = 1,2,...,I; n = 1,2,...,N$$

where X^*_{ni} is the input after adjustment; X_{ni} is the input before adjustment; $[\max(f(Z_i;\widehat{\beta}_n)) - f(Z_i;\widehat{\beta}_n)]$ is the adjustment to exogenous environmental factors; $[\max(\nu_{ni}) - \nu_{ni}]$ denotes that all DMUs are placed on an identical luck level.

Stage three: Adjusted DEA model. The input data that are obtained after the adjustment in stage two are recomputed using the VRS model. At this stage, the input value is exempted from the effects of environmental factors and random errors, and the obtained result objectively and accurately reflects the technical efficiency states of all DMUs.

Stage four: Super-efficiency DEA model. Given the sequencing defect of the traditional BCC model (i.e., its inability to distinguish effective DMUs), this paper applies the super-efficiency DEA model to resequence the efficiency values of effective DMUs and to compare further the effective DMUs. The linear programming formula of the VRS super-efficiency model is constructed as follows based on input orientation:

$$s.t\begin{cases}\min\theta \\ \sum_{j=1,\ j\neq 0}^{n}\lambda_j x_j \leq \theta x_0 \\ \sum_{j=1, j\neq 0}^{n}\lambda_j y_j \geq y_0 \\ \sum_{j=1, j\neq 0}^{n}\lambda_j = 1 \\ \lambda_j \geq 0\left(j=1, 2, ..., n\right)\end{cases}$$

where n is number of DMUs; $x = (x_{1j}, x_{2j}\ldots, x_{mj})^T$ and $y_j = (y_{1j}, y_{2j}\ldots, y_{kj})^T$ represent respectively m input vectors and k output vectors; λ is feasible solution and θ is effective value of DMU.

2.3 Index system and data source

2.3.1 Input and output indexes

Given the practices in the available literature and the effect of human capital on modern ports (Deng, 2012; Wang and Meng, 2013), this paper uses berth number, berth length, and number of port employees as input indexes and uses cargo and container throughputs as output indexes. Given the limitations in the data, this paper replaces the number of port employees by the number of employees in the waterborne transportation industry. The connotation of the modern port is far beyond the operations of the wharf, and the port industry can not be easily distinguished from the waterborne transportation industry. Therefore, the index of the number of employees in the waterborne transportation industry can effectively reflect the status of human capital in the port.

2.3.2 Environmental variable index

To ensure practical significance and considering the SFA goodness-of-fit of many indexes, this paper uses foreign trade dependence degree, density of traffic lines, and financial development, informatization, and industrialization levels of the city where the port is located (direct hinterland) as environmental variables. Foreign trade dependence degree is computed by dividing the total imports and exports of cities by their gross domestic product. Density of traffic lines, which reflects the collection and distribution levels of ports, is calculated by dividing the port-city area with the length of classified roads that have a dominant position in the transportation system of China. Financial development level is computed based on the mean standardized financial correlation ratio of the city and the location quotient of financial practitioners. Informatization level is obtained according to the mean standardized per capita telecommunication income and per capita Internet access rate of a city. Industrialization level reflects the industrialization rate of each city.

2.3.3 Data source

Fourteen ports in YRDR are selected as samples, including large international ports, such as the Shanghai and Ningbo-Zhoushan ports, as well as regional small and medium ports, such as the Yangzhou and Taizhou (Zhejiang) ports. These ports can be classified into coastal and inland river ports based on their type. These ports also have a certain degree of coverage and representativeness. To make the sample closely reflect the reality, the Shanghai and Jiaxing ports are divided into seaport and river port, thereby generating 16 sample ports. The index data are obtained from the China Ports Yearbook (China Port Association, 2009; 2014), the China City Statistical Yearbook, 2009 and 2014 (National Bureau of Statistics of China, 2009; 2014), the local statistical yearbooks and bulletins, the official website of the Ministry of Communications, and the field research materials of some ports.

3 Measurement and Analysis of Port Efficiency in Yangtze River Delta Region

3.1 Traditional DEA analysis

The efficiency levels and scale return states of the 16 sample ports are measured and calculated using Deap 2.1. In 2008, the ports in YRDR had mean comprehensive technical, pure technical, and scale efficiencies of 0.745, 0.779, and 0.951, respectively, notwithstanding the influence of exogenous environmental and random interference factors. Eight ports, namely, the Shanghai seaport, Jiaxing seaport, Jiaxing river port, Suzhou port, Jiangyin port, and Yangzhou port, were in the technological frontier because of their high efficiency values. In 2013, these ports obtained mean comprehensive technical, pure technical, and scale efficiencies of 0.745, 0.685, and 0.854, respectively, while the Jiaxing river port left the technological frontier. In sum, the efficiency value of each port in YRDR declines to a certain extent from 2008 to 2013 (Table 1).

3.2 SFA regression analysis

The SFA regression analysis is performed using Frontier 4.1. The slack quantity of the input variables of each port is treated as a dependent variable, while the five environmental variables (i.e., foreign trade dependence degree, density of traffic lines, and financial development, informatization, and industrialization levels) are treated as explanatory variables. Table 2 presents the regression results. The LR one-sided tests of all six models have passed the significance test at the 5% level, which indicates that SFA regression must be performed at stage two. Except for those in Model 2, all other values of γ are close to 1 and pass the significance test at the 1% level, which indicates that the SFA analysis results are significant, that the influence of the differences resulting from management inefficiency has a predominant role, and that random errors have minimal effects on input slacks. However, the values of γ in Model 2 are close to 1 and pass the significance test at the 5% level, which indicates that the influence of the differences resulting from random errors plays a dominant role. The regression results of the five environmental variables to the three input slacks pass the significance test at the 1% level in most cases, which means that exogenous environmental factors significantly affect the input slacks that are generated by each port. The SFA model regresses the environmental variables on the input slack variables, while the negative regression coefficients indicate that the environmental variables are conducive to input slacks, that is, they facilitate the reduction of the input variable wastes or negative outputs, and vice versa. Specific environmental variables are analyzed as follows:

(1) Foreign trade dependence degree. Foreign trade dependence degree significantly affects the three slack variables, but shows a great change in the direction of the two-time section. In 2008, the foreign trade dependence degree negatively affected the slack variables of quay length and practitioners, thereby suggesting that foreign trade growth promotes the utilization efficiency of quay length and human resources. However, the foreign trade dependence degree positively affected the slack of berth number, thereby indicating that foreign trade growth will result in the extensive management of berths. By contrast, in 2013, the foreign trade dependence

Table 1 Preliminary calculation of port efficiency in the Yangtze River Delta Region

	2008				2013			
	TE	PTE	SE	Scale return	TE	PTE	SE	Scale return
Shanghai seaport	1	1	1	–	1	1	1	–
Shanghai river port	0.079	0.079	0.998	–	0.038	0.103	0.369	irs
Ningbo-Zhoushan port	0.977	1	0.977	drs	1	1	1	–
Hangzhou port	0.235	0.245	0.958	drs	0.252	0.275	0.917	irs
Jiaxing seaport	1	1	1	–	1	1	1	–
Jiaxing river port	1	1	1	–	0.528	0.548	0.963	irs
Wenzhou port	0.335	0.345	0.969	irs	0.207	0.61	0.34	irs
Taizhou (Zhejiang) port	0.365	0.515	0.708	irs	0.185	0.654	0.282	irs
Huzhou port	0.622	0.841	0.739	drs	0.238	0.243	0.98	irs
Suzhou port	1	1	1	–	1	1	1	–
Nanjing port	0.479	0.481	0.997	drs	0.403	0.412	0.978	drs
Nantong port	0.954	1	0.954	drs	0.985	1	0.985	drs
Zhenjiang port	0.91	0.954	0.954	drs	0.41	0.48	0.853	irs
Jiangying port	1	1	1	–	1	1	1	–
Taizhou (Jiangsu) port	0.96	1	0.96	irs	0.638	0.643	0.992	drs
Yangzhou port	1	1	1	–	1	1	1	–

Notes: TE, PTE, and SE represent comprehensive technical, pure technical, and scale efficiencies, respectively, irs represents increasing returns to scale, drs represents decreasing returns to scale, and – represents constant returns to scale

Table 2 SFA regression result of input slacks

	2008			2013		
	Slack of birth number	Slack of birth length	Employment number	Slack of birth number	Slack of birth length	Employment number
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Constant term	1011.56***	–41360.65***	5046.30**	–1184.39***	50871.00***	8076.66***
Foreign trade dependence degree	1.75***	–75856.65***	–16726.91***	–1035.11***	22410.27***	336.20***
Density of traffic lines	–0.01***	0.133	–0.43*	0.02***	–0.19	–0.07***
Financial development level	–0.04***	–5269.853***	518.96	–25.257	–12873.08**	–892.80***
Informatization level	–192.21***	53513.17***	15833.62***	644.79***	–7873.42	–1185.97***
Industrialization level	–1580.37***	–77350.55***	–11832.92***	1402.05***	–97615.04***	–13113.06***
σ^2	1.00E+04***	2.98E+08***	3.92E+07***	8.98E+05***	1.71E+09***	6.27E+05***
γ	0.999***	0.253**	0.800***	0.999***	0.985***	0.999***

Notes: *, **, and *** represent significance at the 10%, 5%, and 1% levels, respectively

degree negatively affected berth slack yet positively affected quay length and practitioners as a result of the financial crisis. A weak growth in foreign trade resulted in the redundant and inefficient use of quays and human resources. Moreover, the port workers faced an unemployment crisis, which drove domestic port operators to focus on enhancing the utilization efficiency of berths.

(2) Density of traffic lines. In 2008 and 2013, the density of traffic lines significantly affected the slack of berth number. Such density changed from negative to positive during this period, which indicates that the traffic conditions in 2008 facilitated the improvements in the collection and distribution systems of ports and in the utilization efficiency of berths. However, the increased traffic accessibility in 2013 resulted in the transfer of many cargo flows from large berths to relatively inefficient small and medium berths, thereby reducing the overall efficiency of these berths. The density of traffic lines negatively affected the slack of employees in both years, thereby suggesting that improved traffic conditions benefitted human resource allocation efficiency. Although the density of traffic lines did not show any obvious effect on the slack of quay length, the change from positive to negative indicates that the improved traffic conditions promoted rather than inhibited the quay (Li and Feng, 2009).

(3) Financial development level. Financial development level significantly and negatively affected the slack of berth number and quay length in 2008, but negatively affected all slacks with an increased significance level, thereby highlighting the importance of financial development in promoting the role of port efficiency in the financial growth of ports and the shipping industry. The construction of ports, the transportation of port logistics, the development of a high-end port service industry, and the investments in human capital are all inseparable from financial support, especially amid the economic restructuring of China and the post-global financial crisis. The function of modern ports must be shifted from traditional sections, such as transit and transfer, to high-end positions in the value chain, such as configuring the elements of finance, information, and other supporting elements in the port industry.

(4) Informatization level. Similar to the density of traffic lines, informatization level can also be reflected in the infrastructure supply function of a city. Table 2 shows that informatization level significantly affects the three slack variables. In 2008, informatization level showed a significant negative relationship with the slack of berth number, thereby suggesting that informatization could effectively improve the berth efficiency. By contrast, the advancements in information technology in 2013 drove large berths to transfer their cargo volume to relatively inefficient small and medium berths, thereby reducing overall berth efficiency. The positive relationship between informatization level and slack of quay length became negative because the advancements in information technology often begin from the large ports. In 2008, the informatization of large berths attracted more cargoes and effectively decreased the utilization efficiency of other shorelines. In 2013, the informatization level of many berths was improved, thereby improving the utilization efficiency of shorelines. Interestingly, informatization level and slack of human capital

showed a positive relationship, thereby indicating that informatization could reduce the efficiency of port workers to a certain extent because traditional employees cannot meet information-related operations immediately in the beginning. However, in the same year, informatization level showed a significant negative effect on the slack of employees, thereby indicating that port workers have been able to make full use of their information resources and allocate their port and shipping recourses rationally after five years of training and adaptation. In other words, information can ultimately enhance the efficiency of human resources.

(5) Industrialization level. Except in Model 4, industrialization level is negatively related to the three input slack variables. This variable has also passed the significance test at the 1% level, which indicates that industrialization rate benefits the reduction of input slacks, that industrial development can always improve port efficiency level, and that the cargo throughput, the resource utilization rate of berths, and the freight volume of industrial products and bulk materials increase along with industrialization level. Nevertheless, industrialization level positively affected the slack of berth number in 2013, which could be explained by the dispersion of cargo flows resulting from the adjustments in the economic structure and industrial transfer of YRDR, thereby leading to excess capacity and decreased efficiency in many berths.

In sum, the environment variables can be divided into traditional (foreign trade dependency degree and industrialization level) and modern elements (density of traffic lines, financial development level, and informatization level). The SFA regression results reveal that the traditional elements are in a transition period and may remain in this stage for a long time, thereby reflecting the fluctuating influence of these variables on port efficiency. By contrast, the modern elements affected the increase in slack variables in 2008 while significantly reduced the efficiency of slacks later on, thereby indicating that these elements will have an important influence on port efficiency in the future.

3.3 DEA analysis after input values adjusted

The values of the input variables are adjusted using the SFA analytical results obtained from stage two. All ports are placed under identical environmental factors and luck levels, and the DEA VRS model is reapplied to estimate the efficiencies and scale return states of the 16 sample ports in YRDR. Table 3 presents the results.

The mean comprehensive technical efficiency of the ports declined between 2008 and 2013. In 2008, the comprehensive technical, average pure technical, and

Table 3 Efficiency after adjustment in the Yangtze River Delta Region

	2008				2013			
	TE	PTE	SE	Scale return	TE	PTE	SE	Scale return
Shanghai seaport	1	1	1	–	1	1	1	–
Shanghai river port	1	1	1	–	0.977	1	0.977	irs
Ningbo-Zhoushan port	1	1	1	–	1	1	1	–
Hangzhou port	0.614	0.618	0.994	drs	0.82	1	0.82	irs
Jiaxing seaport	0.307	0.706	0.435	irs	0.225	0.659	0.341	irs
Jiaxing River port	0.16	0.174	0.920	drs	0.344	0.648	0.531	irs
Wenzhou port	0.434	0.887	0.489	irs	0.250	0.612	0.408	irs
Taizhou (Zhejiang) port	0.331	0.924	0.358	irs	0.186	0.723	0.257	irs
Huzhou port	0.272	0.476	0.572	drs	0.449	0.575	0.780	irs
Suzhou port	0.757	0.827	0.915	drs	1	1	1	–
Nanjing port	1	1	1	–	1	1	1	–
Nantong port	0.543	0.567	0.958	drs	1	1	1	–
Zhenjiang port	0.422	0.423	0.998	drs	0.39	0.555	0.703	irs
Jiangying port	0.577	0.614	0.94	irs	0.406	0.569	0.714	irs
Taizhou (Jiangsu) port	0.419	0.759	0.552	irs	0.460	0.718	0.640	irs
Yangzhou port	0.403	0.698	0.578	irs	0.370	0.882	0.420	irs

Notes: TE, PTE, and SE represent comprehensive technical, pure technical, and scale efficiencies, respectively scale efficiencies of these ports decreased from 0.745, 0.779, and 0.951 to 0.578, 0.73, and 0.794, respectively. The previously recorded high efficiency values of the ports in YRDR were attributed to excellent environment or luck, and the actual efficiency levels of these ports were not as high as they appeared. In 2013, the comprehensive technical efficiency of these ports remained almost the same before and after the adjustment, their scale efficiency reduced from 0.854 to 0.724, while their pure technical efficiency increased from 0.685 to 0.809. Therefore, the loss of efficiency during this period was mainly caused by scale efficiency. In addition, the number of effective DMU before adjustment in 2008 and 2013 are 6 and decreased respectively to 4 and 5 after adjustment, which suggests that external environment and random error factors affect not only the relative efficiency of each DMU but also the proportion of effective DMUs in the entire port system.

The Shanghai seaport (in 2008) and the Shanghai seaport, Ningbo-Zhoushan port, and Suzhou port (in 2013) remained in the frontier of technical efficiency. However, the efficiency values of the Shanghai river, Ningbo-Zhoushan, Hangzhou, Wenzhou, and Nanjing ports in 2008 and those of Shanghai river, Wenzhou, Taizhou (Zhejiang), Huzhou, Nanjing, and Nantong ports in 2013 all increased at different extents because of their increased pure technical efficiency. The efficiency values of the remaining ports declined to a certain extent, which suggested that their high estimated efficiency values in the first stage were caused by favorable environment or luck and did not reflect the actual efficiency of these ports. The scale return of Hangzhou, Jiaxing River, Huzhou, Suzhou, Nantong, and Zhenjiang ports decreased in 2008, which indicated the presence of jammed scale inputs in these ports and the emphasis that these ports have placed on integrating port shipping resources, reducing scale inputs, and achieving smart growth. The other ports continued to expand their scale of investments to an optimum level. All ineffective DMUs showed increasing scale returns in 2013, which could be explained by the declining scale efficiency of the ports.

The efficiency of the sample ports showed an upward trend after comparing their efficiency values between 2008 and 2013. Based on the average efficiency recorded in 2008 and 2013, the comprehensive technical efficiency of these ports increased from 0.578 to 0.617, their pure technical efficiency increased from 0.73 to 0.809, while their scale efficiency decreased from 0.794 to 0.724. On the one hand, the technical efficiency of these ports increased along with the promotion of informatization and the enhancement of technologies. On the other hand, the economic restructuring, industrial transfer, and post-financial crisis effects hindered the scale growth of port cargoes and resulted in a dispersed phenomenon as previously described. Therefore, these ports must increase their scale of investments in the future and maximize the effects of scale and agglomeration economies.

To decompose the efficiency structure, a quadrantal diagram (Fig. 2) is drawn by placing pure technical efficiency on the horizontal axis, placing scale efficiency value on the vertical axis, and setting the critical efficiency value as 0.9 to place the ports in YRDR into four quadrants based on the structural differences in their efficiency values in stage three. In 2008, the first quadrant comprised Shanghai seaport, Ningbo-Zhoushan port, and Nanjing port, all of which having very high pure technical and scale efficiencies. The second quadrant included Zhenjiang and Hangzhou ports, both of which having high scale efficiency yet low pure technical efficiency. Therefore, these ports must focus on improving their port management and technical levels in the future. The third quadrant included Wenzhou port and three other ports that showed great potential for improving their pure technical and scale efficiencies. The fourth quadrant only included Taizhou (Zhejiang) port, which should increase its input scale and improve its centralized resource allocation in the future. In 2013, all these ports experienced changes in their pure technical and scale efficiencies, and seven ports moved across quadrants. Specifically, Suzhou and Nantong ports moved from the second quadrant to the first quadrant after experiencing an increase in their effective DMUs. Zhenjiang, Jiangyin, and Jiaxing river ports moved from the second quadrant to the third quadrant after experiencing a decline in their scale efficiency. Taizhou (Zhejiang) port moved from the fourth quadrant to the third quadrant after experiencing a decline in its pure technical efficiency. Hangzhou port moved from the second quadrant to the fourth quadrant owing to the decrease in its scale efficiency and increase in its pure technical efficiency. In light of these shifts, these ports must also change their development strategies.

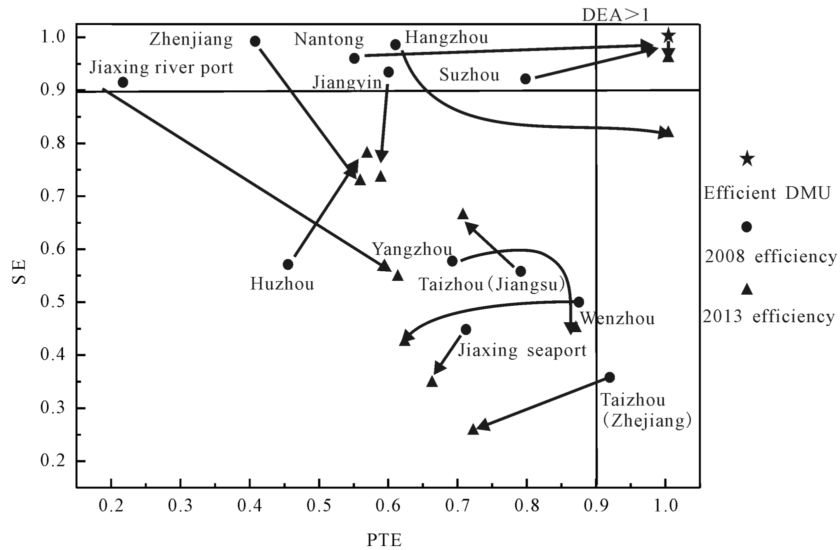

Fig. 2 Pure technical (PTE) and scale efficiency (SE) of ports in Yangtze River Delta Region

3.4 Analysis of super-efficiency DEA results

Although the influence from environmental factors and random errors is eliminated at stage three of the DEA analysis, five effective port DMUs remain unidentified. Therefore, a super-efficiency DEA evaluation of the adjusted data is conducted using MATLAB based on VRS. Table 4 shows that the efficiency values of non-effective port DMUs are unchanged, while the effective port DMUs can be ranked from highest to lowest as follows based on their efficiency values: Shanghai seaport, Shanghai river port, Nanjing port, and Ningbo- Zhoushan port in 2008, and Nanjing port, Shanghai seaport, Suzhou port, Nantong port, and Ningbo- Zhoushan port in 2013. A super-efficiency value higher than 1 indicates that the effective DMUs are still considered effective even after the addition of equal-proportion inputs under the precondition that the input and output values of other DMUs remain unchanged. For example, even when the inputs of Shanghai seaport increase by 153.5% in equal proportion, the port remains in the effective production frontier.

Table 4 The final efficiency and comparison of two groups of ports in the Yangtze River Delta Region

Category	Ports						Mean value	CV
Large ports	Shanghai seaport 2.535 (3.179)	Ningbo-Zhoushan port 1.011 (1.154)					1.773 (2.166)	0.608 (0.661)
Medium ports	Suzhou port 1.565 (0.757)	Nanjing port 3.094 (1.513)	Nantong port 1.160 (0.543)				1.940 (0.938)	0.526 (0.543)
Small ports	Shanghai river port 0.977 (2.784)	Hangzhou port 0.820 (0.614)	Jiaxing seaport 0.225 (0.307)	Jiaxing river port 0.344 (0.160)	Wenzhou port 0.250 (0.434)	Taizhou (Zhejiang) port 0.186 (0.331)	0.443 (0.611)	0.553 (1.198)
	Huzhou port 0.449 (0.272)	Zhenjiang port 0.390 (0.422)	Jiangyin port 0.406 (0.578)	Taizhou (Zhejiang) port 0.460 (0.419)	Yangzhou port 0.370 (0.403)			
Coastal ports	Shanghai seaport 2.535 (3.179)	Ning-Zhoushan port 1.011 (1.154)	Jiaxing seaport 0.225 (0.307)	Wenzhou port 0.250 (0.434)	Taizhou (Zhejiang) port 0.186 (0.331)		0.841 (1.081)	1.197 (1.131)
River ports	Shanghai river port 0.977 (2.784)	Hangzhou port 0.820 (0.614)	Huzhou port 0.449 (0.272)	Suzhou port 1.565 (0.757)	Nanjing port 3.094 (1.513)	Jiaxing river port 0.344 (0.160)	0.912 (0.770)	0.906 (0.982)
	Nantong port 1.160 (0.543)	Zhenjiang port 0.390 (0.422)	Jiangyin port 0.406 (0.578)	Taizhou (Zhejiang) port 0.460 (0.419)	Yangzhou port 0.370 (0.403)			

Note: The data inside and outside the parentheses are for 2008 and 2013, respectively; CV means coefficient of variation

To analyze further the spatial pattern features of the port system in YRDR, this paper follows the method of Liang *et al.* (2009) and classifies the ports in YRDR into two groups, with the first group including large, medium, and small ports and the second group including coastal and river ports. The super-efficiency value is used as a key token parameter in the classification. We obtain several results by calculating the mean value and CV of the port efficiency in each group. For instance, these two groups of ports showed significant discrepancies in 2008. Specifically, the large ports obtained higher efficiency values than the small or medium ports, while the coastal ports obtained higher efficiency values than the river ports. Meanwhile, the large and medium ports obtained a lower CV than the small ports, thereby suggesting a minimal divergence within this group. In 2013, the mean differences between the large and middle ports as well as between the coastal and river ports were obviously reduced, whereas the efficiency of the small ports obviously declined. Apart from a slight enhancement in the coastal ports, the CV of all other ports declined at various degrees and the differences within these groups were narrowed. Specifically, the discrepancies within the group of large, medium, and small ports were significantly lower than those within the group of coastal and river ports.

To discuss further the efficiency pattern of the port system in YRDR and its significance, this paper employs the standard deviation ellipse (SDE) tool in ArcGIS 10.1 for a weighted standard deviation ellipse analysis of two indexes, namely, super-efficiency value and cargo throughput (Fig. 3). As shown in Fig. 3, the two aforementioned groups of ports had significant discrepancies in terms of centrality, directionality, intensity, and distribution (Table 5). First, when comparing the SDE of the super-efficiency value with that of throughput regardless of year (Figs. 3a and 3b), the center of the SDE of efficiency obviously shifted to the northwest direction. At the same time, the ellipse area and the lengths of the long and short axes both increased, thereby suggesting that the efficiency pattern became more balanced while migrating to the northwest direction. The similar spatial pattern appeared between these two groups after several years, thereby supporting the conclusion that the efficiency pattern differs from the throughput distribution. Second, as shown in Fig. 3c, the center of the SDE of efficiency shifted to the northwest direction in 2013. At the same time, the length of the long axis increased, while the length of the short axis and the area of the ellipse decreased. In other words, apart from moving to the northwest direction, port efficiency faced a significant polarization phenomenon in the northwest–southeast direction, which could be attributed to the rapid enhancement of river port efficiency in the northwest direction. Therefore, as an important port cluster and global gateway area, YDDR enhances its port efficiency by moving from the eastern coastal region to the middle and upper reaches of the Yangtze River Belt, which is consistent with the typical function and space evolution of advanced port areas in the world (such as Hong Kong port and Europe ports) (Petti and Beresford, 2009; James and Michael, 2010). In other words, modern port development will inevitably be transformed from traditional transportation hubs to high-end logistic service and supply chain centers, while the aggregation and integration of multiple elements and functions in port areas will make the rapid improvement of port efficiency an inevitable requirement. Therefore, the port system in YRDR must focus not only on transportation segments, such as throughput, but also on the functional transformation and efficiency improvement of ports as well as the construction of a collection and distribution system, a river–ocean combined transportation, and information technology and port financial services.

4 Conclusions and Strategies

4.1 Main conclusions

This paper employs the multi-stage DEA model to study and compare the efficiency values of the major ports in YRDR between 2008 and 2013. This model eliminates the effect of exogenous environmental factors and random errors, distinguishes the sequence of effective port DMUs, and precisely measures the efficiency pattern and evolution of the port system in YRDR. The main findings are presented as follows. First, the port efficiency in YRDR is affected by the management factors and external environment of ports in this area, while the effect of traditional factors, including foreign trade dependency degree and industrialization level, obviously fluctuates as the influence of modern elements, including density of traffic lines, financial development level, and informatization level, significantly increases.

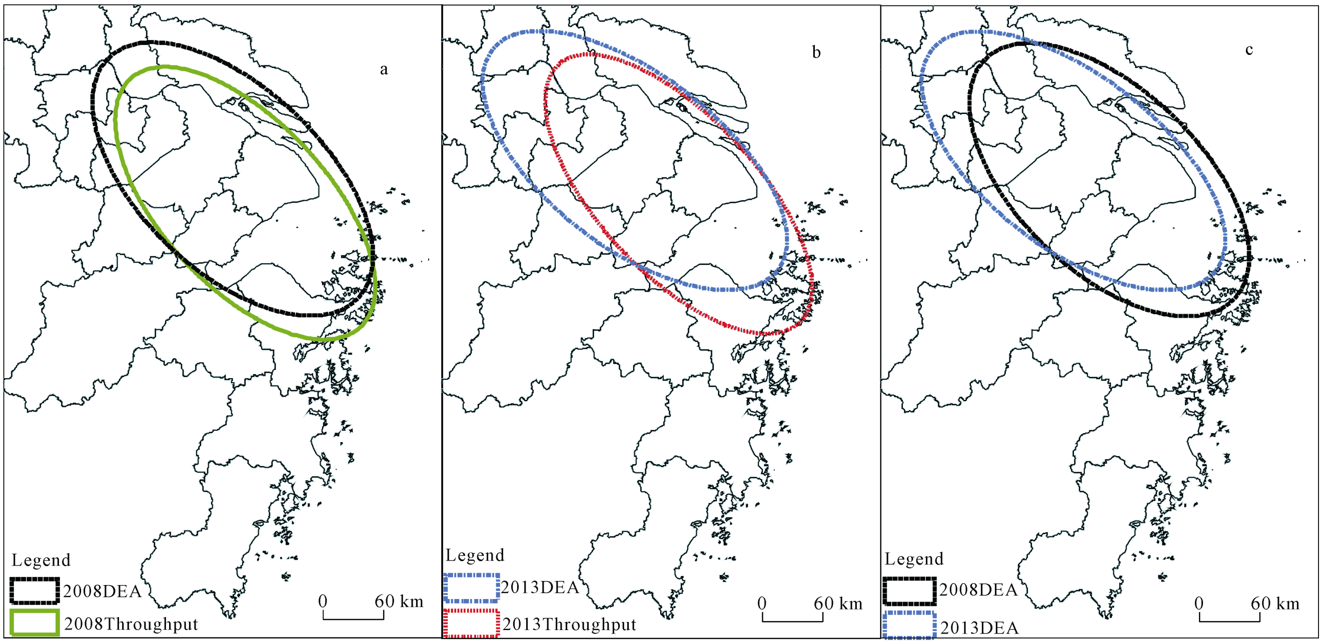

Fig. 3 Standard deviation ellipse analysis result of efficiency and throughput

Table 5 Result of weighted standard deviation ellipse analysis

	Length	Area	Center *X*	Center *Y*	*X* Axis	*X* Axis	Rotation
DEA 2013	8.562	4.755	120.637	31.326	1.796	0.843	127.113
Throughput 2013	8.102	4.205	121.058	30.978	1.709	0.783	137.258
DEA 2008	8.359	4.815	120.995	31.119	1.697	0.903	132.616
Throughput 2008	7.953	4.250	121.098	30.886	1.636	0.826	136.953

Second, the port efficiency values increased along with pure technical efficiency in 2008 and 2013, which could be attributed to the implementation of information and new technologies in the port industry. However, the scale efficiency declined in these years because of the sluggish economic growth and decentralized cargo flow as a combined effect of the economic restructuring, industrial transfer, and post-financial crisis. Third, by taking 0.9 as the critical value and placing pure technical and scale efficiencies on the horizontal and vertical axes of a quadrantal diagram, this paper places the ports in YRDR into four quadrants where each quadrant has a unique developmental direction and discriminative governance strategies. Some ports have moved across quadrants, and the development strategies of ports must be adjusted accordingly. Fourth, the group of large, medium, and small ports and the group of coastal and river ports showed some significant discrepancies in 2008, which diminished in 2013. Similarly, the differences within the groups decreased in 2008 and 2013 as reflected in their CV estimates. The SDE reveals that the port efficiency pattern differs from the throughput pattern, and that the center of the SDE of port efficiency has moved toward the northwest direction. Therefore, the improvements in port efficiency primarily move along the Yangtze River Economic Belt from the eastern region to the western region, while port efficiency has received increasing attention from the authorities.

4.2 Spatial strategies

Based on the analysis results, the port system in YRDR must shift its focus from throughput to efficiency improvement. The port system must also switch from functional repetition to differentiation strategy positioning as well as from separate administration pattern to collective spatial integration development. The following adjustments on the spatial development strategy must be made:

(1) Create an unblocked environment where spatial elements can circulate freely. Therefore, the collec-

tion–distribution system of YRDR, which covers sea–railway joint transportation, river–sea transportation, and roads, railways, and water transportation integration, must be enhanced. The construction of inland port channels and comprehensive logistic networks must also be prioritized. The construction level of port informatization must be improved, and the allocation of elements, particularly high-end port backup elements, in the high, medium, and low segments of the port value chain must be considered. The element-gathering function and important gateway role of ports in the opening up and development of YRDR must also be brought into full play. The administrative division must be weakened, the separate and fragmented port administration system must be overturned, and an unblocked and convenient port element circulation mechanism must be established.

(2) Enhance spatial joint development between ports and cities. The urban surroundings have significant impact on port efficiency, therefore, under the co-impact of changes to external environment like financial crisis post-effect and new domestic economic normal as well as Wintelism and knowledge-based economy, the ′port-city′ relation of port system in YRDR should be reconstructed in time and the simplex port-city connection should be moved towards in-depth port-city interaction so as to promote industrial economy in the port area to transform towards service-oriented economy (Liu *et al.*, 2008). The measures of local conditions must be adjusted, the collaborative and integrated development of ports, industries, and cities must be promoted, and the efficiency and regional competence of ports must be improved by using different spatial scales, taking ports as opening gateways, treating cities as spatial carriers, and offering crucial support to industries.

(3) Propose differentiated port spatial development strategies. By evaluating the super-efficiency of effective port DMUs, decomposing the efficiency of non-effective port DMUs, and analyzing the changes in scale return, this paper finds that in 2008, Nantong port, Suzhou port, and four other similar ports required an increase in technological input, while the other ports required an increase in scale input. However, in 2013, all ports from the second quadrant moved to other quadrants, thereby indicating that the development of the YRDR must continue to increase its investment in scale and focus on developing the effect of scale and agglomeration economies.

(4) Focus on the spatial collaboration of port efficiency. The special structural pattern in YRDR must be organized according to the “axis–spoke” mode while regarding the port group as a subject form. Moreover, an overall plan for resource allocation must be established, the “race to the bottom” in space must be discouraged, and the collaborative efforts must be facilitated to improve the overall efficiency and anti-risk ability of the port system in YRDR. Therefore, a comprehensive port group structure that centers in Shanghai port, surrounded by Zhejiang and Jiangsu ports, and supported by ports along the upper and middle Yangtze River must be established. The Yangtze River Delta port group comprehensive information service platform and an electronic data exchange center must be constructed to facilitate the formation of an inter-port knowledge exchange and information sharing mechanism. Group port shipping resources must be integrated, and the overall efficiency of port groups in YRDR must be enhanced using the knowledge matching and interactive learning mechanisms among interior ports and shipping enterprises (Duranton and Puga, 2004).

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