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EFFICIENCY EVALUATION OF PORTS IN BOHAI RIM REGION BASED ON THREE-STAGE DEA

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Abstract. *As an important window of domestic and foreign trade, port is an important economic resource of a country or region. Based on the background of the new economic normal, exploring port efficiency plays an important role in building a new system of open economy in China. Therefore, this paper uses the three-stage DEA method to make an empirical study on the efficiency of ports in the Bohai Rim region. In the first stage, use the traditional data envelopment analysis (DEA) model to measure efficiency; in the second stage, use the results of the SFA regression model to adjust so that all research objects are in a homogeneous environment; in the third stage, apply the adjustment results of the second-stage investment indicators, and again apply the traditional DEA model to measuring the efficiency to obtain the relative efficiency value excluding the influence of environmental factors and random errors. The results show that the overall level of port efficiency in the Bohai Rim region is relatively high, in which Qingdao Port is always at the forefront of technology. Finally, according to the comparison of the efficiency value of the first stage and the third stage, this paper puts forward some suggestions to improve the port efficiency.*

Keywords: Three-stage DEA, Bohai Rim region, Port efficiency, Environmental factors, Random errors

1. **Introduction.** The strategic position of ports in the Bohai Rim region in the implementation of "The Belt and Road" construction process is obvious, so ports in this region are very worthy of study. Meanwhile the port efficiency directly affects the size of its competitiveness. Therefore, accurate efficiency evaluation of ports can help optimize the port input-output ratio and realize the improvement of port production efficiency.

Research on port efficiency by domestic and foreign scholars began as early as the 1980s. Initially, a single evaluation method or multiple indicators were used to measure port efficiency. For example, port efficiency is studied by linear regression, which quantifies the influence of each variable on port efficiency by establishing a linear regression model [1]. However, the model is too simple to reflect the non-linear relationship among variables, so the results are relatively one-sided. Thence there are fewer studies using this method in the later period. Afterwards, the stochastic frontier analysis method by studying the degree of deviation between ports and efficiency frontier ports is widely used by domestic and foreign scholars [2]. However, the assumptions of this model are more subjective, which will lead to the relative inaccuracy of the measured efficiency values. Compared with the above two parametric methods, the non-parametric method has a more reasonable and objective measurement principle. It mainly includes the balanced scoring method and data envelopment analysis. The balanced scoring method is mainly used to evaluate

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the performance of port enterprises, to evaluate the efficiency from the perspective of finance, customer, innovation and development of port enterprises [3]. Compared with other methods, DEA model has no strict requirements for input and output indicators, and the weights are not influenced by subjective factors. Therefore, it is more suitable for the typical multi-input and multi-output production process of ports. Therefore, since Roll and Hayuth first applied DEA method to port efficiency evaluation [4], DEA models are widely used in several research areas including port efficiency studies [5,6]. Scholars have continued to improve DEA models to accommodate various perspectives in the following studies. For example, the super-efficiency DEA model can further evaluate and rank the decision units with the comprehensive efficiency of 1 [7,8]. In order to improve the DEA model's inability to remove the shortcomings of random errors and environmental variables on efficiency values, Fried proposed a three-stage DEA model, which can make input or output data more accurate to ensure the objectivity and accuracy of efficiency results [9]. Since then, this model has been widely used in various industries research [10,11], and gradually introduced into port related research fields [12-14].

Existing researches on port efficiency in Bohai Rim area rarely consider environmental factors and random errors impacts on port efficiency. Therefore, this paper uses three-stage DEA model to eliminate environmental factors and random errors affecting port efficiency in Bohai Rim region so as to obtain more realistic and accurate port efficiency values. This article enriches the evaluation research on port efficiency in the Bohai Rim region. Based on empirical results, this paper puts forward corresponding countermeasures and suggestions, in order to provide theoretical guidance for future development of port.

2. **Introduction to the Research Methodology.** The three-stage DEA model adopted in this paper adds the theory of stochastic frontier analysis (SFA), which was first proposed by Fried [9]. It is able to remove the effects of environmental factors and random errors on port efficiency, thus making the results more objective and accurate. The model is described below.

1) The first stage DEA model.

The first stage uses the traditional DEA model. This stage selects the input-oriented BCC-DEA model to analyze the original input-output indicators. The model is a mature method, and then its mathematical model is briefly described.

$$\min \left[\theta - \epsilon \left(\sum_{i=1}^{b} S_i^- + \sum_{j=1}^{t} S_j^+ \right) \right], \quad S_i^- \geq 0, \quad S_j^+ \geq 0 \tag{1}$$

$$\text{s.t.} \quad \sum_{r=1}^{a} \lambda_r x_{ir} + S_i^- - \theta x_{ir_0} = 0 \tag{2}$$

$$\sum_{r=1}^{a} \lambda_r y_{jr} - S_j^+ = y_{jr_0}, \quad \lambda_r \geq 0, \quad r = 1, 2, \ldots, a \tag{3}$$

Among them, a is the number of decision units, b is the number of inputs, and t is the number of outputs. S_i^- is the input slack variable. S_j^+ is the value of the output slack variable. x_{ir} is the input variable, y_{ir} is the output variable, and θ indicates the value of the comprehensive efficiency. When $\theta = 1$, the decision unit is valid; otherwise it is invalid.

2) The second stage SFA model.

The second stage uses the SFA method to regress environmental variables. Fried [9] believes that the input and output slack variables obtained by the DEA analysis in the first stage are affected by three factors: environmental factors, random errors and management efficiency. In the second stage, this paper observes the influence of the above three factors separately by constructing an SFA model, thus deriving the input/output redundancy of the decision-making unit caused only by management inefficiency.

The concrete idea is to set an input redundancy regression model for each input so that environmental variables can affect different input redundancy differently.

First establish the slack variable

$$S_{nk} = X_{nk} - X_{nk} \times \alpha, \quad n = 1, \dots, N; \;\; k = 1, 2, \dots, K \tag{4}$$

Among them, X_{nk} is the nth input value of the kth decision unit (DMU). $X_{nk} \times \alpha$ is optimal mapping of the nth input value of k DMU on efficiency frontier surface, and S_{nk} represents corresponding input slack variable.

Secondly, establish regression models of slack variables and environmental variables

$$S_{nk} = f^n(z_k; \beta^n) + v_{nk} + u_{nk}, \quad n = 1, \dots, N; \;\; k = 1, 2, \dots, K \tag{5}$$

S_{nk} is input redundant variable. z_k is exogenous environment variable, and it is observed value of individual DMU management inefficient environment explanatory variables. β^n is an unknown parameter for environmental interpretation variables which need to be estimated. v_{nk} is random error in the production process of the kth DMU at the nth input. u_{nk} is a nonnegative random variable managing inefficient in the production process of the kth DMU at the nth input. v_{nk} is not correlated with u_{nk}, which is mixed error term. Among them, $n = 1, \dots, N$; $k = 1, 2, \dots, K$.

Finally, adjust input variables in two steps.

In the first step, estimating values of statistical noise are estimated by using management inefficiency conditions to separate statistical noise from combinatorial errors, as follows:

$$\widehat{E}(v_{nk} | v_{nk} + u_{nk}) = S_{nk} - z_k \beta^n - \widehat{E}\left(\frac{u_{nk}}{v_{nk}}\right), \quad n = 1, \dots, N; \;\; k = 1, 2, \dots, K \tag{6}$$

In the second step, make upward adjustments to DMU units in better environments and luck with the following formula:

$$X_{nk} = x_{nk} + \left[\max_k \left(z_k \widehat{\beta^n}\right) - z_k \widehat{\beta^n}\right] + \left[\max_k \left(\widehat{v_{nk}}\right) - \widehat{v_{nk}}\right] \tag{7}$$

3) The adjusted DEA model in the third stage.

In the third stage, the adjusted value of each input index is substituted into the BCC model of the first stage, and the efficiency value is recalculated. The efficiency value in this stage excludes the influence of environmental factors and random errors, and can truly and objectively reflect the actual port operation efficiency.

3. **Empirical Analysis.**

3.1. **Selection of indicators and data.**

1) Selection of input and output indicators. The input-output data of the decision unit is the key to the DEA method for measuring port efficiency. Based on the review of existing literature and given the availability of data, container throughput and cargo throughput are selected as output indicators, the number of productive berths and terminal length are selected as input indicators in this paper.

2) Selection of environmental variables. Environmental variables include the natural and social environment. In this paper, the following indicators are selected as environmental variables based on the actual development of ports: 1) hinterland urban GDP; 2) the total amount of import and export; 3) population at the end of the year; 4) the amount of foreign capital actually used.

3) Sample and data sources. In view of the availability and completeness of the data, this paper selects six ports around the Bohai Sea as samples and selects a total of 8 years data from 2011 to 2018. The data mainly come from the "China Port Yearbook", the statistical yearbooks of various provinces, the national data network and the statistical bulletins of national economic and social development of the corresponding cities.

3.2. **Analysis of DEA efficiency value in the first stage.** In the first stage, DEAP2.1 software is used to calculate the comprehensive efficiency (crste), pure technical efficiency (vrste) and scale efficiency (scale) of six ports around the Bohai Sea from 2011 to 2018. The results are shown in Table 1. Among them, QD stands for Qingdao, YT stands for Yantai, RZ stands for Rizhao, DL stands for Dalian, YK stands for Yingkou, and TJ stands for Tianjin.

TABLE 1. The efficiency of six ports in Bohai Rim region from 2011 to 2018

		2011	2012	2013	2014	2015	2016	2017	2018	Mean
QD Port	crste	1	1	1	1	1	1	1	1	1
	vrste	1	1	1	1	1	1	1	1	1
	scale	1	1	1	1	1	1	1	1	1
YT Port	crste	0.517	0.536	0.498	0.513	0.556	0.573	0.446	0.562	0.525
	vrste	0.555	0.577	0.548	0.573	0.627	0.634	0.565	0.817	0.612
	scale	0.932	0.929	0.909	0.896	0.886	0.904	0.789	0.688	0.867
RZ Port	crste	1	1	1	1	1	1	1	1	1
	vrste	1	1	1	1	1	1	1	1	1
	scale	1	1	1	1	1	1	1	1	1
DL Port	crste	0.459	0.466	0.45	0.449	0.448	0.476	0.557	0.515	0.478
	vrste	0.743	0.785	0.814	0.784	0.767	0.793	0.892	0.862	0.805
	scale	0.618	0.594	0.553	0.573	0.584	0.6	0.625	0.597	0.593
YK Port	crste	0.858	0.883	0.833	0.786	0.808	0.841	0.995	0.901	0.863
	vrste	0.873	0.903	0.857	0.822	0.846	0.866	1	1	0.896
	scale	0.982	0.977	0.972	0.956	0.956	0.971	0.995	0.901	0.964
TJ Port	crste	0.735	0.726	0.655	0.688	0.682	0.701	0.793	0.758	0.717
	vrste	1	1	1	1	1	1	0.981	0.936	0.990
	scale	0.735	0.726	0.655	0.688	0.682	0.701	0.808	0.81	0.726
Mean	crste	0.762	0.769	0.739	0.739	0.749	0.765	0.798	0.789	0.764
	vrste	0.862	0.878	0.87	0.863	0.873	0.882	0.906	0.936	0.884
	scale	0.878	0.871	0.848	0.852	0.851	0.863	0.869	0.833	0.858

It can be seen from Table 1, in recent 8 years, without considering the influence of random errors and environmental factors, the average comprehensive efficiency, pure technical efficiency and scale efficiency of the six ports around the Bohai Sea are 0.764, 0.884 and 0.858 respectively, and the overall efficiency of the port is not high. Among them, the comprehensive efficiency of Qingdao Port is 1, which is DEA effective. However, Dalian Port which is also a regional port, has a lower overall efficiency. The main reason is that excessive investment makes ports oversupply. Rizhao Port is also in the effective state of DEA for a long time, indicating that port operation management system has great influence on port efficiency. The low efficiency of Yantai Port is caused by pure technical inefficiency, so managers should appropriately increase technical investment and innovate the management system. The comprehensive efficiency of Yingkou Port is in a high level, and the scale efficiency is slightly lower than the technical efficiency. Managers should further optimize the input-output structure and improve the port operation efficiency.

Tianjin Port has high pure technical efficiency and low scale efficiency, resulting in low comprehensive efficiency. In recent years, its scale efficiency has gradually improved.

3.3. **The second stage SFA stochastic frontier analysis.** The relaxation of each input variable obtained in the first stage is taken as the explanatory variable. And the hinterland city GDP, population, import and export volume and the amount of foreign capital actually used are selected as explanatory variables. This part is calculated by FRONTIER 4.1 software. The results are shown in Table 2.

TABLE 2. SFA regression results of input relaxation variables

Variable	The number of productive berths modulus	Wharf length modulus
Constant term	69.00***(5.28)	7720.00***(4.30)
Hinterland city GDP	2.32E-03*(1.71)	0.614***(2.77)
Population at the end of the year	−3.07E-04(0.0194)	−6.25**(−2.43)
Total import and export	3.25E-07(0.161)	−7.80E-05(−0.263)
The actual use of foreign capital	−1.55E-05**(−2.44)	−1.82E-03*(−1.65)
sigma-squared	4290.00*(1.65)	1.31E+07***(1.16E+07)
gamma	0.963***(39.60)	0.676***(8.22)
log likelihood function	−202.00	−449
LR test of the one-sided error	35.50	9.56

Note: *** means $p < 0.01$, ** means $p < 0.05$, * means $p < 0.1$; the value in parentheses is t value.

It can be seen from Table 2 that most of the parameters in SFA regression model can pass the significance test. The LR values of productive berth number and wharf length likelihood ratio test were significant at 1% and 5% significance level, respectively. The gamma values of redundant variables of production berth number and wharf length are 0.963 and 0.676 respectively, and both are significant at 1% significance level. It shows that it is necessary to use SFA regression model to strip off environmental factors in the second stage of this paper.

It can be seen from the regression results, the hinterland city GDP is a disadvantageous factor to the relaxation variables of the two investments. The reason may be that the growth of GDP will prompt ports to blindly increase investment, which will eventually lead to waste of resources, thereby affecting port efficiency. Population at the end of the year is a favorable factor for the relaxation of the two input variables, indicating that the increase of population will improve the output capacity of unit input. The total amount of import and export is a favorable factor to the relaxation variable of wharf length. It indicates that the increase of total import and export will lead to the increase of port throughput, and then improve the utilization rate of port wharf length resources. However, this environmental variable has a negative impact on the relaxation variable of the number of berths, so that the increase of total import and export volume does not significantly improve the utilization rate of berth resources. The actual use of foreign capital is a favorable factor to the relaxation variables of the two inputs, indicating that the actual use of foreign capital in the port has a good impact on optimizing the port input-output ratio.

It can be seen that the above environmental factors have different directions and degrees of impact on the port. Based on the results of the second stage, this paper will adjust the input data of the ports in Bohai Rim region from 2011 to 2018 to accurately evaluate the efficiency of each port.

3.4. **Analysis of DEA efficiency value after input adjustment in the third stage.** According to the SFA regression results of the second stage, the adjusted input value and the original output value are substituted into the BCC-DEA model again, and the efficiency value of each decision-making unit in the third stage can be obtained. The results are shown in Table 3.

Table 3. Efficiency values of six ports in Bohai Rim region in a homogeneous environment from 2011 to 2018

		2011	2012	2013	2014	2015	2016	2017	2018	Mean
QD Port	crste	1	1	1	1	1	1	1	1	1
	vrste	1	1	1	1	1	1	1	1	1
	scale	1	1	1	1	1	1	1	1	1
YT Port	crste	0.515	0.536	0.506	0.544	0.587	0.593	0.539	0.788	0.576
	vrste	0.943	0.936	0.93	0.927	0.922	0.917	0.85	0.853	0.910
	scale	0.546	0.572	0.544	0.587	0.637	0.647	0.634	0.923	0.636
RZ Port	crste	0.802	0.822	0.824	0.862	0.876	0.873	0.871	0.995	0.866
	vrste	1	1	1	1	1	1	1	1	1
	scale	0.802	0.822	0.824	0.862	0.876	0.873	0.871	0.995	0.866
DL Port	crste	0.74	0.783	0.813	0.787	0.709	0.789	0.844	0.821	0.786
	vrste	0.904	0.912	0.917	0.922	0.854	0.869	0.908	0.88	0.896
	scale	0.818	0.858	0.887	0.853	0.83	0.907	0.93	0.934	0.877
YK Port	crste	0.769	0.811	0.777	0.768	0.789	0.802	0.858	0.833	0.801
	vrste	0.995	0.995	0.999	0.998	0.989	0.997	1	1	0.997
	scale	0.773	0.815	0.778	0.769	0.798	0.805	0.858	0.833	0.804
TJ Port	crste	1	1	1	1	1	0.99	0.926	0.909	0.978
	vrste	1	1	1	1	1	1	0.937	0.943	0.985
	scale	1	1	1	1	1	0.99	0.988	0.963	0.993
Mean	crste	0.804	0.825	0.82	0.827	0.827	0.841	0.839	0.891	0.834
	vrste	0.974	0.974	0.974	0.975	0.961	0.964	0.949	0.946	0.965
	scale	0.823	0.844	0.839	0.845	0.857	0.87	0.88	0.941	0.862

Comparing the efficiency values of the first stage and the third stage, we can see that the efficiency values of each decision unit change in varying degrees after excluding the influence of environmental factors and random errors. From the perspective of the average value of the overall efficiency, the comprehensive efficiency of the third stage is higher than that of the first stage, from 0.764 to 0.834; the pure technical efficiency is also significantly improved, from 0.884 to 0.965; the improvement of scale efficiency is not obvious, from 0.858 to 0.862. And in most cases, the technical efficiency is higher than the scale efficiency, so the port should pay attention to the port scale optimization.

Under the same external conditions, the number of ports whose comprehensive efficiency has always reached DEA effective is reduced to 1. The efficiency of Qingdao Port is still better than that of other ports. After adjustment, the technical efficiency of Rizhao Port remains at 1; however, comprehensive technical efficiency declined slightly. It indicates that environmental variables cover up the mismatch between scale and input-output. The adjusted comprehensive efficiency of Yantai Port is at a low level from 2011 to 2017, the main reason is that the scale efficiency is relatively low, and scale rewards are at incremental stages. It indicates that the construction of hardware facilities limits the improvement of port efficiency. The adjusted Tianjin Port reached DEA effectiveness from 2011 to 2015, indicating that during this period, the input-output structure of Tianjin Port is reasonable, and the previously undervalued port efficiency can be restored. After the adjustment, the scale efficiency of many ports has increased in varying degrees, such as Dalian Port, Yingkou Port and Tianjin Port. It shows that the external environment of the previous three ports limited the port efficiency, affected the utilization rate of port resources, and underestimated the economies of scale of the port.

4. Conclusion and Suggestion.

4.1. Conclusion.

Overall, the port efficiency level in Bohai Rim region is relatively high. However, some ports have the problems of input congestion or low output level, and the waste of port resources is serious. Excluding the influence of environmental factors and random errors, the port efficiency in the Bohai Rim region is mainly affected by the scale efficiency. The promotion of the port efficiency should start from the adjustment of the port scale.

This paper studies the efficiency of six major large ports in the Bohai Rim region. In future studies, we can focus on the operational efficiency of some small ports, and at the same time, we can expand the evaluation index system to a certain extent.

4.2. Suggestion.

Based on the results of empirical analysis, this paper puts forward the following suggestions on the development of port in the Bohai Rim region.

1) Managers should optimize the layout of inter-regional ports and strengthen resource integration, and realize the intensification of resource allocation.

2) The government should increase the tilt of the port collection and distribution facilities and enhance the comprehensive strength of the port. Strengthen the planning and construction of incoming railways and highways.

3) Reasonably introduce funds, improve the port financing system, upgrade loading and unloading equipment to improve loading and unloading efficiency, actively introduce advanced technology, and promote the development of the port towards intelligence and information.

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