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Evaluation of Environmental Efficiency of Chinese Coastal Ports under the Background of Ecological Civilization

-- A Study Based on Three-stage SBM Model

Gengjun Gao[1], Feiyan Zhou[1, *]

[1] Logistics Research Center, Shanghai Maritime University, Shanghai 201306, China

[*] **Corresponding author**: Feiyan Zhou (Email: 1930744929@qq.com)

Abstract: In order to enhance the level of green and sustainable development of the economy, the national policy of ecological civilization construction is proposed. The 14 coastal ports with the top 20 container throughput in China in 2020 are taken as the research objects, and the environmental efficiency evaluation index system of ports is constructed by combining the requirements put forward by ecological civilization, and the three-stage SBM model is applied to measure the environmental efficiency of 14 coastal ports in China from 2012 to 2020. It was found that the overall green development of Chinese coastal ports was good, with half of the ports achieving effective environmental efficiency with a mean value of 0.804 and a large gap in environmental efficiency levels among ports. External environmental variables have significant effects on the environmental efficiency of ports, and the overall environmental efficiency of ports with ineffective environmental efficiency has improved after excluding the effects of external environmental variables and random errors. Therefore, for ports with ineffective environmental efficiency, policy-related contents should be implemented effectively according to the actual situation of the port, and the environmental efficiency of the port should be improved from the perspective of the change and development of the port hinterland city, combining three aspects of local economic conditions, policy environment and cultural awareness.

Keywords: Ecological civilization, Chinese coastal ports, Environmental efficiency evaluation, Three-stage SBM model.

1. Introduction

After the reform and opening up, Chinese economy has developed rapidly, and the development requires a lot of energy and resources, which belongs to the rough and loose development, which has caused a series of problems such as environmental pollution and excessive consumption of resources. The construction of ecological civilization is an important decision made by our government in the face of resource scarcity and environmental degradation. The report of the 19th National Congress proposes that human beings and nature are a community of life, and human beings should respect nature, conform to nature and protect nature.

In today's economic and global trade integration, ocean transportation has become the primary choice for international trade transportation with the advantages of low price and large cargo capacity, occupying more than 90% of the market share. As a transshipment node of the global supply chain, ports account for about 3% of global greenhouse gas emissions. The construction of ecological civilization has put forward requirements for ports in terms of resource utilization, environmental protection, green economy and sustainable development, which has posed great challenges to the development of ports. Measuring the environmental efficiency of ports based on a reasonable evaluation model in the context of ecological civilization is of vital practical significance for ports to save resources, protect the environment, enhance the green development of ports, and promote the construction of ecological civilization in ports and hinterland cities.

2. Literature References

Most of the relevant studies on ecological civilization in China have been conducted from a macro perspective, and some scholars have constructed index systems to evaluate efficiency from the perspective of ecological civilization construction. For example, Yingwen Zhang et al [1] empirically analyzed the efficiency of urban and rural construction land in Beijing using the DEA-Malmquist index method based on the background of ecological civilization construction. Qi Liang et al [2] used the double difference method to analyze that the establishment of ecological civilization pilot demonstration zones has a significant positive impact on eco-efficiency based on the establishment of ecological civilization pilot demonstration zones as a quasi-natural experiment. Yang Dong [3] conducted an empirical study on the efficiency of investment in agricultural environmental regulations in China and its influencing factors and the driving mechanism behind it based on the general context of ecological civilization construction. Zhengen Fan et al [4] constructed the SE-SBM model to statically analyze the green development efficiency and its evolution characteristics of the prefecture-level cities in the ecological civilization test area from 2000-2018, dynamically analyzed its change trend using the GML index, and studied its influencing factors using Tobit regression model. Biao Hu et al [5] used 30 provinces and cities across China as research objects to analyze the spatial and temporal differences of regional environmental efficiency under the perspective of ecological civilization.

Considering the seriousness of port pollution and the necessity of green port construction, some scholars evaluated the environmental efficiency of ports. For example, Jiaguo Liu et al [6] used the super-efficient SBM model and Tobit regression model considering non-desired output to evaluate the efficiency and influence factors of ports in five major FTAs in China. Shun Li et al [7] measured the environmental efficiency of ten container ports in China and examined their external environmental influences using a non-radial, non-angle SBM model and a panel Tobit model.Young-Tae Chang, Junhao Luo et al [8-9] used the SBM-DEA model and selected CO2 emissions as non-expected outputs to evaluate the environmental efficiency of Korean and Chinese ports, respectively. Taehwee Lee et al [10] used the SBM-DEA model to evaluate the environmental efficiency of port cities by considering carbon dioxide, sulfur dioxide and nitrogen oxides together. Xiaoxing Gong et al [11] used the SBM-DEA model to combine different inputs and outputs to evaluate the efficiency of 26 shipping companies considering and not considering negative environmental impacts, environmental adjustment Joon-Ho Na et al [12] considered carbon dioxide as a non-desired output and used an inseparable input-output SBM model to evaluate the environmental efficiency of eight major container ports in China, based on which the carbon dioxide reduction potential of each port was evaluated to improve environmental efficiency. Based on the three-stage SBM model, this paper measures the environmental efficiency of ports based on Chinese coastal ports and proposes environmental efficiency improvement measures in the context of the current situation of port development.

3. Model Construction

Firstly, the SBM model is applied to measure the environmental efficiency values of the port and the input-output slack variables, secondly, the similar SFA regression function is applied to remove the effects of environmental factors and random errors, and finally, the adjusted input variables are again applied to the model in the first stage to measure the environmental efficiency of the port.

3.1. Phase 1: SBM Model

Considering n ports as DMUs, it is assumed that each DMU has m input variables$x = (x_1, x_2 ... x_m) \in R_m$, and produce s_1 desired output variable $y_g = (y_1^g, y_2^g ... y_{s_1}^g) \in R_{s_1}$and s_2 non-desired output variables $y_b = (y_1^b, y_2^b ... y_{s_2}^b) \in R_{s_2}$. Define the matrix as follows:$X = (x_{ij}) \in R^{m \times n} > 0, Y^g = (y_{ij}^g) \in R^{s_1 \times n} > 0, Y^b = (y_{ij}^b) \in R^{s_2 \times n} > 0$, then the set of production possibilities to measure the environmental efficiency of the port is: $P = \{(x, y^g, y^b) | x \geq X\lambda, y^g \leq Y^g\lambda, y^b \leq Y^b\lambda, \lambda \geq 0\}$, and $\lambda \in R^n$. Tone [13] proposed the SBM model considering the non-expected outputs based on the SBM model proposed in 2001, as follows.

$$\theta = min \frac{1 - \frac{1}{m}\sum_{i=1}^{m} s_i^- / x_{i0}}{1 + \frac{1}{s_1 + s_2}(\sum_{k=1}^{s_1} s_k^g / y_{k0}^g + \sum_{r=1}^{s_2} s_r^b / y_{r0}^b)} \quad (1)$$

$$S.t. \quad \begin{aligned} x_0 &= X\lambda + s^- \\ y_0^g &= Y^g\lambda - s^g \\ y_0^b &= Y^b\lambda + s^b \\ \sum_{j=1}^{n} \lambda_j &= 1 \\ s^- \geq 0, s^g &\geq 0, s^b \geq 0, \lambda \geq 0 \end{aligned} \quad (2)$$

Where s^-, s^g, s^b represents the input, desired output, and non-desired output slack variables; λ denotes the weight variable; and the subscript 0 represents the DMU of the evaluation. the objective function θ is between 0 and 1 and is strictly monotonically decreasing with the slack variables. When θ is 1 and the slack variable is equal to 0, the DMU is valid. Otherwise, the DMU is non-valid.

3.2. Phase 2: Similar SFA regression model

Similar SFA regression models were constructed using the input indicator slack variables calculated in the first stage as explanatory variables and external environmental variables and random errors as explanatory variables.

$$s_{ni} = f(Z_i; \beta_n) + v_{ni} + \mu_{ni}; \ i = 1,2, ..., I; \ n = 1,2, ..., N \quad (3)$$

Where s_{ni} denotes the slack value of the i input in the n DMU; Z_i denotes the environmental variable; β_n denotes the environmental variable coefficient; $v_{ni} + \mu_{ni}$ denotes the mixed error term, v_{ni} denotes the random disturbance term; and μ_{ni} denotes the management inefficiency term. $v \sim N(0, \sigma_v^2)$ denotes the random error term which means the effect of random disturbances on the input slack variables, and μ is the management inefficiency term which means the effect of management inefficiency on the input slack variables, which is assumed to obey a normal distribution truncated at zero, $\mu \sim N^+(0, \sigma_\mu^2)$.

The purpose of using SFA regression is to remove the effects of environmental and random factors efficiency evaluation, so that all DMUs are in the same external environment. The adjustment equation is as follows.

$$X_{ni}^A = X_{ni} + [max(f(Z_i; \beta_n)) - f(Z_i; \beta_n)] + [max(v_{ni}) - v_{ni}]; \ i = 1,2, ..., I; \ n = 1,2, ..., N \quad (4)$$

Where X_{ni}^A denotes the adjusted input; X_{ni} denotes the input before adjustment; $[max(f(Z_i; \beta_n)) - f(Z_i; \beta_n)]$ denotes adjustment for external environmental factors; and $[max(v_{ni}) - v_{ni}]$ denotes placing all DMUs at the same level of luck.

Further separating management inefficiency, the separation formula for management inefficiency is:

$$E[\mu / \varepsilon] = \sigma_* [\frac{\phi(\frac{\lambda\varepsilon}{\sigma})}{\Phi(\frac{\lambda\varepsilon}{\sigma})} + \frac{\lambda\varepsilon}{\sigma}] \quad (5)$$

What's more, $\sigma_* = \frac{\sigma_\mu \sigma_v}{\sigma}$, $\sigma = \sqrt{\sigma_\mu^2 + \sigma_v^2}$, $\lambda = \frac{\sigma_\mu}{\sigma_v}$.

The separation of the random error terms is given by:

$$E[v_{ni} | (v_{ni} + \mu_{ni})] = S_{ni} - f(Z_i; \beta_n) - E[u_{ni} | (v_{ni} + \mu_{ni})] \quad (6)$$

3.3. Phase 3: Adjusted SBM model

The adjusted input-output variables are used to measure the environmental efficiency of each DMU again. At this time, the environmental efficiency has removed the influence of environmental factors and random factors, and is a relatively real and accurate environmental efficiency value.

4. Variable Selection and Data Sources

4.1. Variable selection

In order to improve the overall efficiency of the port, it is necessary to consider various environmental factors and establish a scientific and effective input-output model and the corresponding input-output evaluation system. The construction of ecological civilization strives to minimize the impact on the environment while economic development. The proposed construction of ecological civilization has led to changes in the environmental efficiency of ports. At the same time, the level of environmental efficiency of ports is also a key factor affecting the process of ecological civilization construction. To summarize, in order to implement China's 13th Five-Year Plan and the goal of building ecological civilization proposed in the 19th Party Congress, this paper takes the concept of sustainable development as the starting point and constructs a port environmental efficiency evaluation system, which mainly focuses on the "input-output" process of ports. The system mainly focuses on the "input-output" process of ports. To a certain extent, the process of "input-output" affects the utilization of natural resources and the degree of environmental pollution, while ecological civilization constrains the environmental efficiency of coastal ports and makes coastal ports consider more pollution problems and resource allocation when evaluating environmental efficiency. From the input point of view, in addition to the infrastructure input in port production, the energy consumption in the process of port production also needs to be considered. From the output point of view, the resource and environmental impact brought by port production is mainly increased, i.e. not only the positive impact of the port throughput and the resulting economic output needs to be considered, but also the negative impact of the damage caused to the environment in the process of its development needs to be considered. Therefore, this paper selects berth length, berth number and integrated energy consumption per unit throughput as input variables, container throughput and cargo throughput as desired output variables, and carbon dioxide emission per unit throughput, nitrogen oxide emission per unit throughput, sulfur oxide emission per unit throughput and solid waste emission per unit throughput as non-desired output variables.

In addition to constructing the input-output index system of environmental efficiency of coastal ports, it is also necessary to construct the external environmental index system. For the selected external environmental indicators, they should not only have an impact on the environmental efficiency of the port, but also not be subjectively controlled by the port. From the perspective of economic development, the expansion of the economic scale of the hinterland cities can bring financial input to the development of the port, thus expanding the output of the port and the accompanying environmental pollution problems. At the same time, the level of economic development will improve the people's living standards, and then the public's consumption philosophy will change to green preferences, thus promoting the upgrading of the port's industrial structure. From the perspective of political construction, by promulgating laws and regulations, industry standards and other forms can improve the environmental quality management ability of hinterland cities, increase the investment and attention to environmental protection in hinterland cities, so as to enhance the awareness of energy saving and emission reduction of port enterprises and reduce the emission of pollutants. Secondly, the port's throughput can be increased by improving the level of opening to the outside world and introducing foreign direct investment to expand the port's cargo sources, however, from the scale it may increase the port's pollutant emissions, which in turn affects the port's environmental efficiency. From the perspective of cultural construction, higher human capital helps to improve the technical level of ports, and human capital is the key to economic growth and technological progress. Ports can not only improve resource utilization rate and output level by improving production technology level, but also reduce pollutant emission per unit of throughput by upgrading pollution control technology and clean technology, thus making the environmental management level of ports rise and realizing the coordination of economic and environmental development, which in turn affects the environmental efficiency of ports. In this paper, we select five external environmental variable indicators: total import and export of hinterland cities, the number of employees in environmental management, the proportion of tertiary industry, the greening coverage of built-up areas, and the number of undergraduate students in schools.

4.2. Data sources

Considering the representativeness of the research subjects, 16 coastal ports ranked in the top 20 in terms of container throughput in 2020 are selected, namely Shanghai Port, Ningbo-Zhoushan Port, Shenzhen Port, Guangzhou Port, Qingdao Port, Tianjin Port, Xiamen Port, Yingkou Port, Dalian Port, Beibu Gulf Port, Rizhao Port, Lianyungang Port, Fuzhou Port, Yantai Port, Tangshan Port Quanzhou Port. Since the data of Fuzhou Port and Beibu Gulf Port are seriously missing, the remaining 14 coastal ports from 2012 to 2020 are finally selected as the research objects in this paper. With the concept of green ports, Chinese coastal ports are paying more and more attention to energy saving and emission reduction. By evaluating the environmental efficiency of coastal ports, the environmental efficiency differences and development trends of Chinese coastal ports can be more clearly defined.

The data of input and output variables used in the evaluation of environmental efficiency of Chinese coastal ports are mainly from the 2013-2021 China Statistical Yearbook, China Port Yearbook, China City Statistical Yearbook, the statistical yearbooks of the provinces and core cities where they are located, the 2012-2020 National Economic and Social Development Statistical Bulletin, the official websites of the ports and the statistical data of the Chinese Ministry of Transport. In this paper, the hinterland city refers to the core city where the port is located, and the data of external environmental variables are mainly obtained from the 2013-2021 China City Statistical Yearbook, the statistical yearbooks of the core cities in the port hinterland, the environmental situation bulletin of each city, etc.

5. Empirical Analysis

This paper evaluates the environmental efficiency of 14 coastal ports in China from 2012-2020 based on the three-stage SBM model, compares the environmental efficiency differences of each port from a cross-sectional perspective, and analyzes the competitiveness of each port in order to provide countermeasure suggestions for the future development of each coastal port.

5.1. Phase 1: Empirical results of SBM model

The MAXDEA Ultra8.21 software was used to measure the environmental efficiency of 14 coastal ports in China from 2012 to 2020, and the results are shown in Table 1. Without considering the influence of environmental variables and random errors, the mean value of environmental efficiency is 0.804, seven coastal ports have a mean value of 1, and there is still some room for improving the environmental efficiency of the remaining coastal ports.

Table 1. Port Environmental Efficiency comparing

Port	Stage	2012	2013	2014	2015	2016	2017	2018	2019	2020	Mean
Dalian	First	0.586	0.547	0.631	0.597	0.657	0.689	0.655	0.466	0.323	0.573
	Third	0.777	0.788	0.78	0.703	0.749	0.735	0.723	0.544	0.45	0.694
Guangzhou	First	1	1	1	1	1	1	0.858	0.538	0.676	0.897
	Third	1	1	1	1	1	1	0.888	0.747	0.813	0.939
Lianyungang	First	0.571	0.603	0.62	0.589	0.625	0.587	0.542	0.542	0.5	0.576
	Third	0.554	0.554	0.579	0.547	0.557	0.557	0.548	0.543	0.521	0.551
Ningbo-Zhoushan	First	1	1	1	1	1	1	1	1	1	1
	Third	1	1	1	1	1	1	1	1	1	1
Qingdao	First	1	1	1	1	1	1	1	1	1	1
	Third	1	1	1	1	1	1	1	1	1	1
Quanzhou	First	0.234	0.201	0.203	0.234	0.25	0.248	0.234	0.236	0.213	0.228
	Third	0.291	0.262	0.259	0.278	0.279	0.268	0.256	0.253	0.225	0.263
Rizhao	First	1	1	1	1	1	1	1	1	1	1
	Third	1	1	1	1	1	1	1	1	1	1
Xiamen	First	0.648	0.546	0.782	0.572	0.742	0.741	0.758	0.533	0.549	0.652
	Third	0.589	0.56	0.664	0.567	0.685	0.703	0.696	0.55	0.551	0.618
Shanghai	First	1	1	1	1	1	1	1	1	1	1
	Third	1	1	1	1	1	1	1	1	1	1
Shenzhen	First	1	1	1	1	1	1	1	1	1	1
	Third	1	1	1	1	1	1	1	1	1	1
Tangshan	First	1	1	1	1	1	1	1	1	1	1
	Third	1	1	1	1	1	1	1	1	1	1
Tianjin	First	1	1	1	1	1	1	1	1	1	1
	Third	1	1	1	1	1	1	1	1	1	1
Yantai	First	0.478	0.45	0.564	0.688	0.683	0.535	0.474	0.443	0.434	0.528
	Third	0.629	0.582	0.652	0.642	0.637	0.532	0.549	0.507	0.602	0.592
Yingkou	First	0.769	0.803	0.935	0.956	1	0.936	0.874	0.528	0.478	0.809
	Third	0.895	0.847	0.878	0.825	0.795	0.885	0.839	0.525	0.493	0.776
Mean	First	0.806	0.797	0.838	0.831	0.854	0.838	0.814	0.735	0.727	0.804
	Third	0.838	0.828	0.844	0.826	0.836	0.834	0.821	0.762	0.761	0.817

5.2. Phase 2: Empirical results of the similar SFA model

In this paper, the three input index slack variables calculated by the SBM model considering non-expected output in the first stage are used as explanatory variables, and the selected external environmental variables are used as explanatory variables, and the regression results are shown in Table 2. The slack variables values of berth length, number of berths, and integrated energy consumption per unit of throughput are all less than 1. The slack variable value of integrated energy consumption per unit of throughput is greater than 0.9, and the values of berth length and number of berths pass the significance test at the 1% level, although they are less than 0.9. The results indicate that management inefficiency has a greater effect on the input slack variables compared to random error. The LR one-sided error test values for each input slack variable passed the significance test at the 1% level, rejecting the hypothesis that there is no management inefficiency term, which leads to the conclusion that external environmental variables can have an effect on the input slack values, so the second stage of regression analysis was conducted using a similar SFA model, excluding the effects of environmental variables and random errors.

According to the regression results in Table 2, it can be seen that most of the five external environmental indicators can pass the 1% significance test on the input slack variables, so the external environmental indicators selected in this paper have a significant effect on the input slack variables of environmental efficiency in Chinese coastal ports. If the regression coefficient of environmental indicators on input slack variables is negative, it indicates that the increase of environmental indicators is conducive to the reduction of input slack variables, which can promote the improvement of environmental efficiency; on the contrary, if the regression coefficient of environmental indicators is positive, it indicates that the increase of environmental indicators will make input slack variables increase, which will make environmental efficiency decrease.

Table 1. Three Scheme comparing

Variables	Berth length slack variable	Number of berths slack variable	Slack variable for combined energy consumption per unit throughput
Constant term	-5001.5358***	-16.3350	-0.4243
	(-7.6909)	(-1.2277)	(-0.4243)
Total imports and exports	-7147.0256***	-68.9402***	1.7140*
	(-13.9536)	(-3.0155)	(1.7140)
Number of employees in environmental management	5785.6272***	102.5236***	-2.3815**
	(16.7813)	(2.9047)	(-2.3815)
Percentage of tertiary industry	4614.7906***	-34.7859	-7.5731***
	(42.3711)	(-1.2486)	(-7.5732)
Greening coverage rate of built-up areas	3508.2292***	81.1351***	0.8850
	(2.9656)	(4.5138)	(0.8851)
Number of undergraduates in school	732.9603*	-43.6277	4.5938***
	(1.8380)	(-1.1174)	(4.5938)
σ^2	66125322***	7254.2389***	20.0095***
	(65979990)	(10.9855)	(20.0096)
γ	0.8511***	0.8280***	0.9791
	(54.6205)	(31.4727)	(1.0362)
LR unilateral error	97.1506 ***	56.7960***	311.4638***
	-5001.5358***	-16.3350	-0.4243

Note:***, **, * respectively represent significant at the 1%, 5%, and 10% levels, () inside is T-test value.

From the table, it can be seen that the increase of total import and export is conducive to reducing the slack variables of berth length and number of berths, which will also increase the slack variables of integrated energy consumption per unit of throughput and promote the improvement of environmental efficiency of the port to a certain extent. The increase in the number of environmental management employees helps to reduce the port's investment in energy, but increases the investment in other aspects. The increase in the proportion of tertiary industry helps the port to deepen energy saving and emission reduction and improve the environmental efficiency of the port, however, with the increase of cargo, the blind expansion of the port will also lead to the waste of resources, which leads to the decrease of the environmental efficiency of the port. The increase of greening coverage in the built-up area helps the port to save energy and reduce emissions, however, too much investment will cause a certain degree of waste of resources, which is not conducive to the sustainable development of the port, thus leading to the decline of environmental efficiency. The increase in the number of undergraduate students will improve the level of education in the city, thus attracting more population inflow, making the population scale expand, further expanding the demand for cargo, and the increase in the scale of port throughput may lead to an increase in port pollutants, thus leading to a decrease in environmental efficiency.

5.3. Phase 3: Empirical results of the adjusted SBM model

The adjusted data are brought into the SBM model considering the undesired output for calculation and measured using MAXDEA Ultra8.21 software. The results are shown in Table 2. It can be seen that after excluding the effects of external environmental variables and random errors, the environmental efficiency of Chinese coastal ports changed more significantly, and the overall environmental efficiency values of ports increased. In terms of time series, after excluding the influence of external environmental variables and random errors, the overall environmental efficiency mean value of ports shows a fluctuating decline, with the adjusted environmental efficiency mean value being larger than the pre-adjustment environmental efficiency mean value during 2012-2014 and 2018-2019, and the adjusted environmental efficiency mean value being smaller than the pre-adjustment environmental efficiency mean value during 2015-2017.

For the ports in the first echelon in the first phase, the environmental efficiency value of the ports remains unchanged and is still equal to 1, which is still at the effective level of environmental efficiency. For the ports in the second echelon in the first stage, the mean environmental efficiency value of Yingkou port decreases and changes from the fluctuating upward trend in the first stage to the fluctuating downward trend from 2012 to 2016, indicating that the geographical location of Yingkou port and external environmental variables have a more obvious driving effect on the environmental efficiency of the port. The mean value of environmental efficiency of Guangzhou port has increased, which is mainly due to the fact that after excluding the influence of external environmental variables and random errors in the third stage, the influence of transport supply-side reform and the new crown epidemic of Guangzhou port is reduced, which is mainly reflected in the fact that all ports with non-effective environmental efficiency in 2018-2020 have increased to some extent. For ports in the third echelon in the first stage, the average environmental efficiency values of Dalian, Yantai and Quanzhou ports have increased, while those of Lianyungang and Xiamen ports have decreased. The environmental efficiency of Dalian Port, Yantai Port and Quanzhou Port in the third stage in 2012 was higher than that of the first stage, and the overall environmental efficiency values showed a fluctuating downward trend, indicating that Dalian Port, Coastal Port and Quanzhou Port were more influenced by the external environment. Putting aside the influence of transportation supply-side reform and the new crown epidemic on the environmental efficiency of ports, the average environmental efficiency values of ports in the third stage changed from fluctuating up in the first stage to fluctuating down in 2012-2016, so although the external environmental variables and the random disturbance term have a suppressive effect on the environmental efficiency values, in terms of the overall trend, the environmental efficiency values of Chinese coastal ports show a fluctuating upward trend. The mean environmental efficiency values of Lianyungang Port and Xiamen Port decreased, indicating that the external environment of Lianyungang Port and Xiamen Port had a significant contribution to the environmental efficiency values of the ports. In general, compared with the initial port environmental efficiency in the first stage, the port environmental efficiency excluding external environmental variables and random errors in the third stage has both rising and falling cases, i.e., the external environmental variables have different effects on the port environmental efficiency. Therefore, ports need to develop measures to improve the environmental efficiency of ports according to local conditions and policy environment.

6. Conclusion

In this paper, a three-stage SBM model is applied to evaluate the environmental efficiency of 14 coastal ports with the top ranking of container throughput in China in 2020 for the period 2012-2020. The following conclusions are drawn：

(1) The overall green development of China's coastal ports is relatively balanced, and half of them can achieve effective environmental efficiency, indicating that these seven ports have reasonable input-output configuration, high operation management level and good green port construction level. As a whole, the mean value of environmental efficiency is 0.804, and the overall pollution control is good. 14 coastal ports have environmental efficiency values between 0.201 and 1, and there is a large gap in green development among ports.

(2) The environmental variables significantly affect the environmental efficiency of the ports and conceal the real green development status of the ports. After the similar SFA regression model eliminates the influence of external environmental variables and random errors, the ports with high level of green development still show effective environmental efficiency after adjustment, and the environmental efficiency values of ports that do not reach effective environmental efficiency change significantly, and the overall environmental efficiency mean value is improved and the development trend is smoother than before.

Based on the above findings, the following recommendations are made：

(1) Improve the efficiency of its own operation by expanding the scale of enterprises and production, so as to achieve the optimal production scale. At the same time, determine the current status and advantages of the port, increase the integration of regional port resources, strengthen the cooperation of the ports in the region, make the ports develop in a staggered direction towards specialization and differentiation, and further realize the synergistic development of regional ports. Thus, it attracts cargo sources, improves the scale of the port's throughput and enhances the environmental efficiency value of the port.

(2) The green development of ports and the development of hinterland cities promote each other. The development of the port in the direction of green port involves many departments, and different departments should strengthen the synergistic linkage on the green development of the port, effectively implement the relevant contents of the policy according to the actual situation of the port, provide financial subsidies for some key projects of energy conservation and emission reduction, give targeted assistance and reasonable rewards and punishments to avoid wasting resources.

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