Analysis of Port Efficiency Considering Carbon Emissions: A Case Study of Seven Ports in the Guangdong Hong Kong Macao Greater Bay Area

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Abstract: With the development of ports, the problems of port operation inefficiency and environmental pollution caused by them have gradually become the focus of attention. Based on the input-output panel data of seven major ports in the Guangdong-Hong Kong-Macao Greater Bay Area from 2016 to 2020, considering the impact of carbon emissions, this paper applies the DEA-Undesirable model to statically analyze the efficiency of seven ports in the Guangdong-Hong Kong-Macao Greater Bay Area, and then further applies the Malmquist index decomposition to dynamically analyze the port efficiency in the Guangdong-Hong Kong-Macao Greater Bay Area. The conclusion shows that some ports in the selected objects have reached the level of high efficiency; Some ports have not yet reached high efficiency levels; The overall efficiency has not yet reached the high efficiency level, but the development is on the rise and will continue to improve in the future.

Keywords: carbon emissions, port efficiency, SBM-Undesirable model, Malmquist index

1. INTRODUCTION

The Guangdong-Hong Kong-Macao Greater Bay Area (hereinafter referred to as the "Greater Bay Area") is one of the regions with the highest degree of openness and the strongest economic vitality in China, and has an important strategic position in the overall national planning. Ports are one of the engines of regional economic development, and the development of them plays an important role in regional economic and social development. With the rapid advancement of the construction of the Greater Bay Area, the port construction of the Greater Bay Area has become more mature, and the efficiency of port has significantly improved. However, from a practical perspective, there are still many problems with the ports in the Greater Bay Area, and there is still room for further improvement in their efficiency. At the same time, with the continuous development of ports, environmental problems derived from ports have gradually received attention, and carbon emissions have become an important indicator that cannot be ignored in the evaluation of port efficiency. Therefore, under the premise of considering carbon emissions, port efficiency analysis can objectively evaluate port operations and provide reference for future development planning of ports, which has positive practical significance.

In recent years, many scholars have conducted extensive research on port efficiency, mainly focusing on DEA analysis and the construction of its derivative models. Based on the traditional DEA model, Li Gongming introduced constraint variables and virtual decision units to improve

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the DEA model and measure the operational efficiency of Tianjin Port [1]. Based on the SBM-DEA model, Luo Junhao et al. set CO2 emissions as an unexpected indicator and analyzed the impact of CO2 emissions on the efficiency of eight container ports in China [2]. Jia Peng, Lu Lin, and others considered carbon emissions in the output variables and used the super efficiency SBM model and Malmquist index decomposition to study the efficiency and its cross period changes of 16 ports from 2010 to 2018 [3]. Liu Yong et al. incorporated unexpected outputs into the network DEA model and divided the efficiency evaluation process of ports into two stages: green production evaluation and specialized production evaluation of goods. They proposed a two-stage model for container port efficiency evaluation [4]. Tovar and Wall estimate environmental efficiency for a cross section of 28 Spanish Ports in 2016 using an output-oriented directional distance frontier with carbon dioxide emissions [5]. Djordjevic et al. use a novel two-stage non-radial DEA model to evaluate the environmental efficiency of Dublin Port considering landward and seaward operation [6].

In previous studies on port efficiency, although carbon emissions were often considered, they were rarely combined with specific regional development situations. Based on the previous research methods, this paper uses the SBM- Undesirable model to conduct a static analysis of the input-output panel data of seven major ports in the Great Bay Area from 2016 to 2020, and then further introduces Malmquist index decomposition to study the dynamic changes in efficiency. Objectively evaluate the development status of ports in the Greater Bay Area through efficiency analysis from both static and dynamic perspectives.

2. RESEARCH METHODS

Data envelopment analysis (DEA) is a kind of efficiency evaluation method with multiple inputs and outputs, which can evaluate the relative efficiency of each decision making unit (DMU) through the situation of inputs and outputs. This method not only eliminates the need to set the relationship between functions in advance, but also assumes the weights of various indicators, making it suitable for static efficiency evaluation problems. According to the assumption of whether returns to scale is variable, it can be divided into constant returns to scale (CRS) and variable returns to scale (VRS).

This article considers using the SBM-Undesirable model to more effectively evaluate the static efficiency including carbon emissions. Meanwhile, in order to further consider the dynamic changes in efficiency, Malmquist index decomposition is introduced for dynamic evaluation of efficiency.

2.1 SBM-Undesirable model

$$min\rho = \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^{x^-}}{x_{i0}}}{1+\frac{1}{s_d+s_u}\left(\sum_{d=1}^{r}\frac{s_d^{y^+}}{y_{d0}}+\sum_{u=1}^{v}\frac{s_u^{b^-}}{b_{u0}}\right)} \qquad y_0=\sum_{j=1}^{n}\lambda_j y_{dj}-s_d^{y^+} d=1,2,\dots r$$

$$s.t. x_0=\sum_{j=1}^{n}\lambda_j x_{ij}+s_i^{x^-}, i=1,2,\dots m \qquad b_0=\sum_{j=1}^{n}\lambda_j b_{uj}+s_u^{b^-}, u=1,2,\dots v$$

$$\lambda \geq 0, s_i^{x^-} \geq 0, s_d^{y^+} \geq 0, s_u^{b^-} \geq 0 \qquad (1)$$

In equation (1), $s_i^{x^-}$, $s_d^{y^+}$ representing inputs and expected outputs respectively, $s_u^{b^-}$ represent undesired outputs; λ is the weight vector, ρ is the efficiency value of each decision unit, and meets

$0 \leq \rho \leq 1$; For a specific decision unit, when $\rho = 1$, it means that the decision unit is at the forefront of production and is in an optimal state of efficiency.

2.2 Malmquist Index

Malmquist index is a measurement method to measure the dynamic change of efficiency in DEA model, which is combined with the DEA method to measure the TFP (total factor productivity) change in adjacent periods, analyze the efficiency of the same DMU in different periods, and consider the efficiency after all inputs are converted into output.

The model expression is:

$$\mathrm{M}(x^{t+1}, y^{t+1}, x^t, y^t) = \left[\frac{D_C^t(x^{t+1}, y^{t+1})}{D_C^t(x^t, y^t)} \times \frac{D_C^{t+1}(x^{t+1}, y^{t+1})}{D_C^{t+1}(x^t, y^t)}\right]^{\frac{1}{2}} \quad (2)$$

In equation (2), x^{t+1}, y^{t+1}, x^t, y^t are representing the input and output of the t+1 period and the t period respectively. $D_C^t(x^t, y^t)$, $D_C^t(x^{t+1}, y^{t+1})$ represents a distance function over time. When M>1, TFP shows an upward trend; When M<1, TFP showed a downward trend; When M=1, TFP does not change.

Malmquist TFP can be decomposed into the Technology Change Index (Techch) and the Technology Efficiency Change Index (Effch), which can be further broken down into the Pure Technology Efficiency Change Index (Pech) and the Scale Efficiency Change Index (Sech).

3. PORT EFFICIENCY MEASUREMENT

3.1 Construction of evaluation index system

This article selects seven representative ports (Hong Kong, Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, and Zhaoqing) in the Greater Bay Area from 2016 to 2020 as DMUs.

The DEA model measures efficiency based on DMU input and output data. In previous literature on port efficiency, port length, number of loading and unloading equipment, and number of berths were commonly used as input indicators; Cargo throughput is a commonly used output indicator, and some literature uses container throughput, port profit, etc. as output indicators.

This article considers the impact of environmental pollution on port efficiency. Therefore, in the output indicators, carbon emissions are added in addition to the cargo throughput. At the same time, the investment indicators include berth length, number of berths, and number of motor boats, reflecting the infrastructure investment situation of the port.

In this article, data on berth length, number of berths, number of motor ships, and cargo throughput are sourced from statistical yearbooks of various citys, Guangdong Provincial Statistical Yearbook, and Hong Kong Port Statistical Yearbook. The carbon emissions are calculated based on the average annual standard coal consumption in the port statistical yearbook.

3.2 SBM-Undesirable static analysis

The SBM-Undesirable model was used to measure the port efficiency of the seven ports in the Greater Bay Area from 2016 to 2020, and the results are shown in Table 1.

Table 1. Efficiency Values of Each Port from 2016 to 2020

	TE	PTE	SE	TE	PTE	SE	TE	PTE	SE
	2016			2017			2018		
Hongkong	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Guangzhou	0.772	1.000	0.772	0.725	1.000	0.725	0.783	1.000	0.783
Shenzhen	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Zhuhai	0.688	1.000	0.688	0.727	1.000	0.727	0.698	1.000	0.698
Foshan	0.304	0.640	0.475	0.328	0.626	0.524	0.374	0.662	0.565
Huizhou	0.479	1.000	0.479	0.421	0.788	0.535	0.596	0.864	0.690
Zhaoqing	0.280	1.000	0.280	0.340	1.000	0.340	0.402	1.000	0.402
AVERAGE	0.646	0.949	0.671	0.649	0.916	0.693	0.693	0.932	0.734
	2019			2020			Average		
Hongkong	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Guangzhou	0.776	1.000	0.776	1.000	1.000	1.000	0.811	1.000	0.811
Shenzhen	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Zhuhai	0.736	1.000	0.736	0.670	1.000	0.670	0.704	1.000	0.704
Foshan	0.418	0.713	0.587	0.420	0.730	0.576	0.369	0.674	0.545
Huizhou	0.635	1.000	0.635	0.631	0.893	0.706	0.552	0.909	0.609
Zhaoqing	0.408	1.000	0.408	0.552	1.000	0.552	0.396	1.000	0.396
AVERAGE	0.710	0.959	0.734	0.753	0.946	0.786	0.690	0.940	0.724

1) Overall analysis

Table 1 shows the technical efficiency, pure technical efficiency and scale efficiency of the seven ports in the Greater Bay Area from 2016 to 2020. If environmental factors and random disturbance factors are not considered, the overall average technical efficiency value of the seven ports in the Greater Bay Area within five years is 0.690, the pure technical efficiency value is 0.940, and the scale efficiency value is 0.724. Overall, the pure technical efficiency of ports in the Greater Bay Area has reached a high level, with advanced port technology, clean energy use, and port enterprise management level reaching a high level. On the contrary, although the scale efficiency has reached 0.724, there is still ample room for improvement compared to technical efficiency. The overall scale inefficiency of ports in the Greater Bay Area is severe, and the efficiency of port investment and resource allocation is not high.

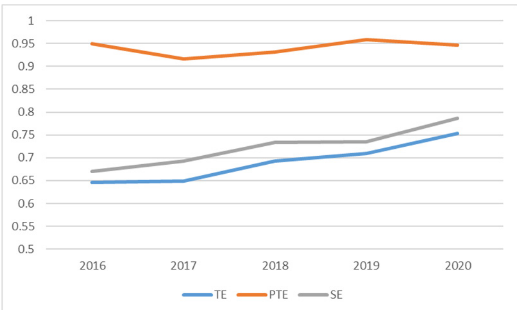

Fig. 1. Average Efficiency Values of Seven Ports in the Greater Bay Area from 2016 to 2020

As shown in Fig. 1, Based on the annual trend chart of average technical efficiency, average pure technical efficiency, and average scale efficiency of ports in the Greater Bay Area, the following conclusions can be drawn from the analysis:

The average technical efficiency and average scale efficiency values have been increasing year by year from 2016 to 2018, indicating that with the gradual progress of the construction of the Greater Bay Area, the overall technical efficiency of the ports in the Greater Bay Area has gradually improved and reached a high level. The average pure technical efficiency value has always been at a high level above 0.9, indicating that as a window area for national opening-up, the Greater Bay Area has achieved a level of leading technology investment and management in the vast majority of regions in the country. Since 2018, there has been a significant decline in both average technical efficiency and average scale efficiency, indicating that scale inefficiency still affects port technical efficiency. There is still significant room for improvement in the investment level and resource allocation efficiency of ports in the Greater Bay Area.

2) Analysis of each ports

From Table 1, it can be seen that the average technical efficiency, average pure technical efficiency, and average scale efficiency of the two major ports in Hong Kong and Shenzhen have all reached 1, which is at the forefront of technology. This indicates that the operational efficiency and technical level of both ports have reached the theoretical optimal state. This result is in line with the positioning of Hong Kong as an international trade center and Shenzhen as a window city for opening up to the outside world.

Except for the fact that the scale efficiency of Guangzhou Port did not reach the optimal level in 2019, all other indicators have reached the optimal level. This indicates that Guangzhou Port is approaching its optimal state. The abnormal situation in 2019 originated from the port expansion project. With the promotion of expansion and the gradual improvement of supporting technology and management, Guangzhou Port returned to its optimal state in 2020.

From 2016 to 2020, the pure technical efficiency of Zhuhai Port reached its optimal level, indicating that the technical operation level and supporting management of Zhuhai Port have reached their optimal level. Due to the poor level of scale efficiency, the technical efficiency has always been below 0.75 except for 2018. According to past analysis, the shallow shoreline of Zhuhai Port is long, and the number of deepwater terminals is limited, which can easily lead to low scale efficiency.

Foshan Port has shown poor performance in various efficiency indicators, and there has been no significant improvement in all efficiency indicators between 2016 and 2020. According to analysis, Foshan Port is adjacent to Guangzhou, and its development scale has been limited for a long time. Due to being in the same hinterland as Guangzhou Port, there is severe homogenization competition, which greatly leads to poor performance in all efficiency indicators.

The pure technical efficiency of Huizhou and Zhaoqing ports reached a relatively optimal or optimal level from 2016 to 2020, but due to the limited size of hinterland cities and overall demand, the scale efficiency of each year is at a relatively low level, ranging from 0.6 to 0.75, thus affecting the technical efficiency of Huizhou and Zhaoqing ports.

3.3. Dynamic analysis by the Malmquist index

In order to conduct in-depth research on the efficiency changes of the seven ports in the Greater Bay Area over time and the movement process of production boundaries, this section introduces the Malmquist index to measure the various efficiency change indices of the ports. The measurement results are shown in Table 2 and Table 3.

Table 2. The Malmquist Index and Decomposition of Port Efficiency for the Seven Ports in the Greater Bay Area from 2016 to 2020

year	effch	techch	pech	sech	tfpch
2016-2017	1.048	1.037	0.985	1.065	1.087
2017-2018	1.043	0.996	1.033	1.009	1.038
2018-2019	0.919	1.247	1.025	0.897	1.146
2019-2020	0.986	1.03	0.996	0.991	1.016
Average	0.998	1.073	1.009	0.989	1.071

Table 3. The Malmquist Index and Decomposition of Port Efficiency for the Seven Ports in the Greater Bay Area from 2016 to 2020

firm	effch	techch	pech	sech	tfpch
Hongkong	1.000	1.201	1.000	1.000	1.201
Guangzhou	1.000	1.055	1.000	1.000	1.055
Shenzhen	1.000	1.015	1.000	1.000	1.015
Zhuhai	0.968	1.021	1.000	0.968	0.988
Foshan	1.048	1.04	1.077	0.973	1.090
Huizhou	0.964	1.065	0.990	0.974	1.027
Zhaoqing	1.007	1.126	1.000	1.007	1.134
Average	0.998	1.073	1.009	0.989	1.071

1) Overall analysis of dynamic changes

From Table 2, the efficiency of ports in the Greater Bay Area increased by an average of 7.1% from 2016 to 2020, with an average decrease of 0.2% in effch and an average increase of 7.3% in techch. This indicates that under the combined influence of technological efficiency and technological progress efficiency, the efficiency of ports has significantly improved. From 2016 to 2018, effch increased by 4.8% and 4.3% respectively year by year, indicating a significant improvement in port efficiency from 2016 to 2018. The effch decreased by 8.1% and 1.4% respectively for two consecutive years from 2018 to 2020, indicating a significant decline in port efficiency from 2018 to 2020.

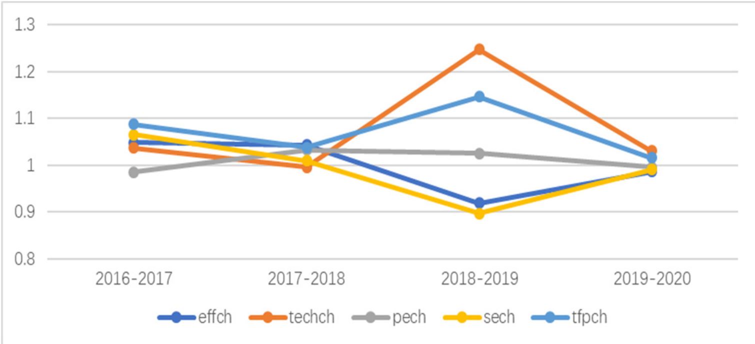

Fig. 2. The Malmquist Index and Decomposition of Port Efficiency at Seven Ports in the Greater Bay Area from 2016 to 2020

From Fig. 2, the trend of TFP and techch from 2016 to 2020 is the same, and the magnitude of TFP change is smaller than that of techch, indicating that TFP is affected by the effch and has not been able to maintain maximum synchronization with techch. At the same time, the trend of effch is basically consistent with the trend of sech, indicating that sech is the main factor affecting effch. As shown in the figure, pech remains basically stable, which further proves the correctness of the above discussion. The above analysis indicates that port innovation technology has a good development momentum in various ports in the Greater Bay Area, and should maintain the development momentum and continue to improve in the future. On the contrary, sech continues to decline, indicating that the efficiency of port resource allocation is still insufficient. In the future, it is necessary to further improve the level of port management, improve the efficiency of port resource allocation, reduce port scale inefficiency, and thereby improve port efficiency.

2) Analysis of each port

Table 3 shows the average Malmquist index and its decomposition of the seven ports in the Greater Bay Area from 2016 to 2020. They are: Hong Kong Port 1.201, Guangzhou Port 1.055, Shenzhen Port 1.015, Zhuhai Port 0.988, Foshan Port 1.09, Huizhou Port 1.027, Zhaoqing Port 1.134, and the average Malmquist index of the seven ports in the Greater Bay Area is 1.071. Among them, the Malmquist index value of Hong Kong Port significantly exceeds the average level of the Greater Bay Area, the Malmquist index value of Zhaoqing Port moderately exceeds the average level of the Greater Bay Area, the Malmquist index value of Foshan Port slightly exceeds the average level of the Greater Bay Area, the Malmquist index value of Guangzhou Port is slightly lower than the average level of the Greater Bay Area, and the Malmquist index value of Huizhou Port and Shenzhen Port is moderately lower than the average level of the Greater Bay Area, The Malmquist index value of Zhuhai Port is significantly lower than the average level of the Greater Bay Area. Rank the Malmquist Index of the seven ports in the Greater Bay Area from high to low, in the order of Hong Kong Port, Zhaoqing Port, Foshan Port, Guangzhou Port, Huizhou Port, Shenzhen Port, and Zhuhai Port. There is huge room for improving the efficiency of Zhuhai Port, followed by Shenzhen Port and Huizhou Port. There is still room for improvement in the efficiency of Guangzhou Port, while Hong Kong Port and Zhaoqing Port continue to develop and maintain port efficiency.

The average techch of seven ports in the Greater Bay Area from 2016 to 2020 are: Hong Kong Port 1.201, Guangzhou Port 1.055, Shenzhen Port 1.015, Zhuhai Port 1.021, Foshan Port 1.04, Huizhou Port 1.126, and Zhaoqing Port 1.126. Among them, Hong Kong Port's techch value significantly exceeds the average level of the Greater Bay Area, Zhaoqing Port's techch value moderately exceeds the average level of the Greater Bay Area, Huizhou Port and Shenzhen Port's techch slightly lower than the average level of the Greater Bay Area, Foshan Port's techch value moderately lower than the average level of the Greater Bay Area, Shenzhen Port Zhuhai Port's techch is significantly lower than the average level in the Greater Bay Area. The techch of all ports exceeds 1, indicating outstanding technological innovation performance in the Greater Bay Area, and technological progress is the main factor in improving port efficiency in the Greater Bay Area.

Except for Huizhou Port, all six ports have pech exceeding 1. This indicates that there is still room for improvement in the pech of Huizhou Port, and there is still room for development in the operational efficiency of technical fields such as port equipment. The remaining ports' pech remained stable, indicating that the development of port technology has steadily improved and continues to improve.

The sech of Foshan Port, Zhuhai Port, and Huizhou Port are less than 1, indicating that compared to Hong Kong Port, Shenzhen Port, and Guangzhou Port, which have good early advantages, such as long development time, mature management models, and technology applications. Foshan Port and Huizhou Port have a short development time, and the development scale has not formed. The resource allocation efficiency has not reached a relatively optimal level, and there is still room for development in terms of scale efficiency. Zhuhai Port has a long history of development, but it is limited by its geographical environment, with many shallow shoals and mud, and a limited number of deep-water docks, which greatly affects its sech.

4. CONCLUSION

Based on the input-output panel data of seven ports in the Greater Bay Area from 2016 to 2020, considering carbon emissions, this paper applies the SBM-Undesirable model and Malmquist index to conduct static and dynamic analysis on the port efficiency of the Greater Bay Area, and analyzes it from the overall and individual perspectives. The conclusions are as follows:

From a static perspective, the overall efficiency of ports in the Greater Bay Area has not reached a high level. Specifically, there are not only old and high-level ports such as Hong Kong Port, Shenzhen Port, and Guangzhou Port, but also Foshan Port, Huizhou Port, and Zhaoqing Port that have gained development opportunities with the construction of the Greater Bay Area. In the future, various ports will maintain mutual influence, promote together, and form a good synergy to build a high-level port group in the Greater Bay Area, injecting vitality into the construction of the Greater Bay Area.

From a dynamic perspective, the overall Malmquist index in the Greater Bay Area has maintained an upward trend. After decomposition, the techch of each port shows an upward trend, indicating a good development momentum in the technology field in the Greater Bay Area. Meanwhile, some secondary ports have a significant downward trend in sech, indicating that sech is the main component affecting the Malmquist index.

The ports in the Greater Bay Area are an important engine for promoting high-quality development in the region, and there is a long way to go for future development. The evaluation results of this article are consistent with the current development status of port clusters in the Greater Bay Area, and clarify the future development trend of ports in the Greater Bay Area. According to the plan, in the future, we will continue to focus on deepening the strategic positioning and development direction of the three major international hub ports of Hong Kong, Guangzhou, and Shenzhen. Other ports will accelerate resource integration and allocation based on their own development status, forming a multi-level, collaborative, and complementary development pattern of ports. At the same time, we will accelerate the construction of smart ports and strive to build a world-class port cluster that is safe, efficient, smart, green, innovative and open.

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