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Research on Regional Waterway Transportation Efficiency Based on DEA and Malmquist Index Model: Taking Guangxi Beibu Gulf as an Example

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Abstract: To study the efficiency of regional waterway transportation, taking Guangxi Beibu Gulf as an example, this paper constructs the input-output index system from 2016 to 2020, using DEA-Malmquist index model to analyse the water transport efficiency of three port cities in Beibu Gulf region. The results show that the overall efficiency of waterway transportation in Guangxi Beibu Gulf region is DEA invalid, which is mainly restricted by scale efficiency. From 2016 to 2020, the total factor productivity of the Beibu Gulf region generally showed a slight downward trend, and technological progress was the main factor affecting total factor productivity. Therefore, appropriately expanding the scale effect, improving the utilization rate of water transport resources, and encouraging the construction of high-tech projects and the circulation of technical talents are conducive to promoting the output efficiency of water transport.

1. Introduction

Transportation, an important research topic in the 21st century, provides important support for socio-economic activities and regional development infrastructure. As a part of the integrated transportation system, water transportation enjoys a unique advantage in the transportation of goods in large volumes over long distances. Thanks to its huge capacity, small land occupation, low variable cost and little energy consumption and pollution, it becomes a key strategic resource for sustainable socio-economic development. As the core strategic node of China's "Belt and Road Initiative", Guangxi Beibu Gulf region shoulders the heavy responsibility of goods circulation and trade between Guangxi and other countries. Establishment of China-Asean Free Trade area brings new development opportunity for Beibu Gulf port. Transportation efficiency means the relative relationship between the input of transport resources and the actual effective output, which provides a comprehensive measure of the operation and development potential of the transportation system [1]. Transportation efficiency has become a key performance index in the transportation industry, receiving extensive attention from numerous scholars. The use of data envelopment analysis (DEA) model is free from limitation of the specific form of production functions or the distribution of random variables, which can appropriately measure transportation efficiency with production characteristics of "multiple inputs and multiple outputs" [2]. Therefore, DEA model is recommended for assessing the waterway transportation efficiency.

At present, scholars mainly evaluate transportation efficiency from three angles. The first is the degree of coordination between the transportation system and national, social and regional economies. Based on DEA cross-efficiency, Li Yong et al. constructed a coupled coordination degree model to measure the coupling coordination degree between transportation and regional economic development in seven regions of China. The spatial and temporal evolution characteristics of the coupling coordination degree were analyzed [3]. Using the super-efficiency DEA model, Song Min et al. measured the integrated transportation efficiency of 37 cities in the Yangtze River Delta and Guangdong-Hong Kong-Macao Greater Bay Area. Spatial econometric model was introduced to analyze the spillover effect of greater integrated transportation efficiency on economic growth [4]. Second, transportation efficiency is evaluated based on the coordination of resource settings between different transportation modes. Barnum et al. proposed that public transportation in first-tier urban areas usually consists of multiple transportation modes, and the overall efficiency of urban public transportation can be effectively estimated only when comprehensive consideration is given to the technical efficiency and resource allocation efficiency of each major transportation mode. The improved DEA model was used to calculate the efficiency of different transportation modes in economically prosperous areas [5]. Based on the time efficiency of different transportation modes and the income liquidation method of carbon emission, Mao Baohua et al. identified the multimodal transportation mode with high transportation efficiency and green low-carbon. The appropriate resource allocation weight coefficients were determined in light of the actual multimodal transport environment [6]. The third is to measure the transportation system efficiency and its decomposition. Referring to the SBM model and DEA window analysis method, Fan Yuejiao et al. measured the efficiency of the five major transport corridors of the Maritime Silk Road to analyze the output deficiencies and input problems of the five corridors [7].

Most scholars choose the third approach to measure transportation efficiency, with rich research results achieved in urban public transportation, ports, roads, and railways [8], but relatively little research has been done on waterway transportation efficiency. Hence, this paper draws on the existing research results to study the recent waterway transportation development level of cities in the Beibu Gulf region, and takes fuzzy matter element method to measure the waterway transportation level in Guangxi region. Waterway transportation efficiency restricts waterway transportation development. DEA-Malmquist index model was built to measure the waterway transportation efficiency in 2016-2020 to find out the dominant factors affecting efficiency. Based on this, countermeasures and suggestions are proposed to improve the waterway transportation efficiency in the Beibu Gulf region.

2. Research Methodology and Data Sources

2.1. DEA Model

DEA method is an operations research method developed by Charnes et al. [9] based on the concept of relative efficiency, which demonstrates absolute advantages in evaluating the efficiency of multi-input and multi-output decision-making operations. Different from parametric methods, DEA uses local approximation method to construct frontier surface evaluation decision units based on actual data, thus preventing influence from subjective factors. Seen from the current practical application, the most widely used and most influential models are still CCR and BCC models. Pairwise programming corresponding to linear programming of the CCR model can be illustrated as:

$$Min\left\{\theta-\varepsilon\left(\hat{e}^{T}S^{-}+\hat{e}^{T}S^{+}\right)\right\}s.t.\begin{cases}\sum_{j-1}^{n}X_{j}\lambda_{j}+S^{-}=\theta X_{0}\\ \sum_{j-1}^{n}Y_{j}\lambda_{j}-S^{+}=Y_{0}\\ \lambda_{j}\geq 0,\ j=1,2,\ldots,n\\ S^{-}\geq 0,S^{+}\geq 0,\end{cases} \tag{1}$$

Where: θ is the planning target value, $\lambda_j(j=1,2,\ldots n)$ is the weight of the planning decision variable, $S^- =(S_1^-,S_2^-,\ldots,S_m^-)T$ and $S^+ =(S_1^+,S_2^+,\ldots,S_m^+)T$ represent the relaxation variable vector. Compared to CCR model, BCC model has additional $\sum_{j=1}^{n}\lambda_j=1$ in the above constraints. In practical applications, the DEA model is mostly based on the CCR model, and the efficiency values of different DMUs are calculated according to the input-based CCR model. θ is a comprehensive measure and evaluation of the resource allocation capacity and utilization efficiency of a DMU. In this paper, higher θ value indicates higher water transportation efficiency.

2.2. Malmquist Index

Malmquist was first proposed by the Swedish economist and statistician Malmquist [10]. On its basis, Caves et al. used the index to measure the total factor productivity (TFP) variation index. Charnes et al. [11] combined the index with DEA model. The DEA-based Malmquist index can effectively deal with multiple-input and multiple-output data sets, which allows decomposition of total factor productivity (TFP) to study the sources of TFP growth.

Suppose there are s decision units in period t, the i-th input of the r-th decision unit is x_{ir}^t, and the j-th output of the r-th decision unit is $y_{ir}^y(j=1,2,\ldots)$. The distance function of Malmquist index according to the DEA model equation is $D^t(x_r^{t+1},y_r^{t+1})$, and then the Malmquist index for the rth decision unit from period t to period t+1 is determined as follows.

$$M(x_r^{t+1},y_r^{t+1},x_r^t,y_r^t)=\frac{D^t(x_r^t,y_r^t)}{D^{t+1}(x_r^{t+1},y_r^{t+1})}\times\left[\frac{D^{t+1}(x_r^t,y_r^t)}{D^t(x_r^{t+1},y_r^{t+1})}\times\frac{D^{t+1}(x_r^{t+1},y_r^{t+1})}{D^t(x_r^t,y_r^t)}\right]^{\frac{1}{2}} \tag{2}$$

When M index > 1, it suggests the total efficiency presents an upward trend as time passes. When M index = 1, it means that the total efficiency will not change over time; when M index < 1, the total efficiency lowers. When the technical efficiency and technical progress change more than 1, it indicates that it is the root of TFP growth. Otherwise, it is the root of TFP decrease.

2.3. Index Selection and Data Source

To study waterway transportation efficiency in the Guangxi Beibu Gulf region, with three port cities as the unit and taking the time span of 2016-2020, the panel data was collected for indexes from two dimensions of water transportation construction inputs and efficiency outputs of port cities (shown in Table 1) to reflect the water transportation level and its efficiency. The DEA-Malmquist index model was used to measure the waterway transportation efficiency of the Beibu Gulf region and its influencing factors to investigate its evolution pattern.

Table 1: Measurement index of waterway transportation level

Input	Fixed asset investment (100 million yuan)	X_1
	Wharf length (m)	X_2
	Number of people engaged in storage, transportation and postal industry (10,000 people)	X_3
Output	Cargo turnover (100 million tkm)	X_4
	Waterway freight volume (10,000 t)	X_5

Water transportation statistics in China are inferior to road or railway transportation in terms of volume, scale and accuracy, which brings some difficulties to quantitative research of water transportation efficiency. Therefore, considering the research purpose, the model requirements and the data availability, the input indexes are used to indicate the manpower, port infrastructure and capital invested in regional waterway transportation. Storage, transportation and postal industries are regional labor-intensive industries. Wharf length plays a key role in supporting the waterway transportation infrastructure elements, which suggests geo-differentiation in waterway transportation. The total investment in fixed assets is selected as capital input. Output indexes fully reveal the unevenness of waterway transportation development, which are mainly assessed from the waterway transportation scale in each port city. Waterway freight volume and cargo turnover capacity intuitively reflect the scale characteristics of waterway transportation in each region.

Water transportation data statistics have time lag, so this paper selects the 2016-2020 data from the "Guangxi Statistical Yearbook (2017-2021)" and the statistical bulletin of national economic and social development of Beibu Gulf cities in 2016-2020.

3. Empirical Analysis and Results

3.1. Static Analysis of Waterway Transportation Efficiency in Beibu Gulf Region

Using DEAP2.1 software, the waterway transportation efficiency of Beibu Gulf region and the decomposition results are obtained, as shown in Table 2.

Table 2: Efficiency measurement results of the Beibu Gulf region in 2016-2020

City	Efficiency	2016	2017	2018	2019	2020	Mean value
Fangchenggang	Comprehensive technical efficiency	1	0.975	1	1	1	0.995
	Pure technical efficiency	1	1	1	1	1	1
	Scale efficiency	1	0.975	1	1	1	0.995
	Returns to scale	-	Irs	-	-	-	
Beihai	Comprehensive technical efficiency	0.981	0.99	1	1	1	0.9942
	Pure technical efficiency	1	1	1	1	1	1
	Scale efficiency	0.981	0.99	1	1	1	0.9942
	Returns to scale	irs	irs	-	-	-	
Qinzhou	Comprehensive technical efficiency	1	1	0.963	0.984	0.994	0.9882
	Pure technical efficiency	1	1	0.969	0.997	1	0.9932
	Scale efficiency	1	1	0.994	0.987	0.994	0.995
	Returns to scale	-	-	drs	drs	drs	

A comprehensive efficiency value of 1 indicates that DEA is effective and the inputs and outputs are optimal. Table 2 reveals that Fangchenggang city only has a comprehensive technical efficiency value less than 1 in 2017. Beihai city has low comprehensive technical efficiency and insufficient production efficiency in 2016 and 2017. Qinzhou City exhibits input-output imbalance in the last three years, with invalid comprehensive technical efficiency in both 2018 and 2019. The above data indicates that Fangchenggang has the best water transportation efficiency, Qinzhou has the lowest mean regional production efficiency, and Beibu Gulf region needs improvement in overall water transportation production efficiency.

The pure technical efficiency reflects the input factor utilization degree. The mean value of pure technical efficiency of both Fangchenggang and Beihai is 1, indicating optimal allocation of the input factors without need for improvement. Qinzhou has a low value of pure technical efficiency in 2018 and 2019, and the degree of technologization has room for improvement.

Scale efficiency intuitively reflects the degree of allocation between input and output factors. A scale efficiency of less than 1 means insufficient inputs or redundant capacity. Fangchenggang was slightly deficient in input-output in 2017, showing insufficient scale efficiency and increasing returns to scale. Beihai City also presented low scale efficiency value and incremental returns to scale in 2016 and 2017. Qinzhou showed insufficient scale efficiency and diminishing returns to scale in 2018-2020, with uneven input and output resources in waterway transportation in recent years.

3.2. Differential Adjustment of Waterway Transportation System in the Beibu Gulf Region

Based on the efficiency assessment, further analysis is made on the cities failing to reach the optimal comprehensive efficiency, with the results shown in Table 3.

Table 3: Differential adjustment of the waterway transportation system in the Beibu Gulf region, 2016-2020

		Output index		Input index		
	Year	Cargo turnover (tkm)	Waterway freight volume (t)	Fixed asset investment (yuan)	Wharf length (m)	Number of people engaged in storage, transport and postal services (people)
Fangchenggang	2017	0	0	0	0	-4
Beihai	2016	-1000	0	0	0	3
	2017	0	0	30000	0	-2
Qinzhou	2018	0	-282820	9117245000	453	145
	2019	0	-82050	474290400	133	23
	2020	0	0	-9733	0	0

Insufficient input in Fangchenggang in 2017 is manifested in labor force. Analysis based on the incremental returns to scale shows that appropriate increase in the input of employees can enlarge its scale efficiency. As for Beihai in 2016, insufficient cargo turnover and excessive input of employees lead to incremental returns to scale. In 2017, Beihai blindly added 30, 000 yuan investment in fixed assets and reduced the labor force, resulting in its low returns to scale. Qinzhou had low water transportation efficiency in 2018-2020, showing uneven input and output. In 2018 and 2019, due to the excessive investment amount, the expansion of wharf and a large increase in the number of employees, problems of input redundancy, low scale efficiency values, insufficient pure technical efficiency values occurred, with waterway freight volume well below the target value. In 2020, significant improvement yielded some results, the number of employees shrank, but the investment in fixed assets was insufficient compared to the previous two years. These data fully suggest the need for increasing input utilization rate, improving technology and reducing cost in future development of Guangxi Beibu Gulf region.

3.3. Dynamic Analysis of Waterway Transportation Efficiency in Port Cities

The Malmquist index model is used to measure the changes of total factor productivity (TFP), with the results shown in Table 4 and Table 5.

Table 4: Malmquist index changes and decomposition of waterway transportation in the Beibu Gulf region, 2016-2020

Year	Technical efficiency	Technical progress	Pure technical efficiency	Scale efficiency	Total factor productivity index
2016-2017	1.018	0.954	1	1.018	0.972
2017-2018	1.067	0.979	1	1.067	1.044
2018-2019	0.958	0.965	1	0.958	0.924
2019-2020	1.107	0.956	1	1.107	1.058
Mean value	1.0375	0.9635	1	1.0375	0.9995

Table 5: Changes and decomposition of the Malmquist index for waterway transportation in the Beibu Gulf region, 2016-2020

		2016-2017	2017-2018	2018-2019	2019-2020	Mean value
Fangchenggang	Technical efficiency	1	1	1	1	1
	Technological progress	0.916	1.115	0.966	0.981	0.9945
	Pure technical efficiency	1	1	1	1	1
	Scale efficiency	1	1	1	1	1
	Total factor productivity index	0.916	1.115	0.966	0.981	0.9945
Beihai	Technical efficiency	1.055	1.213	0.879	1.356	1.12575
	Technological progress	0.986	0.96	1.022	0.956	0.981
	Pure technical efficiency	1	1	1	1	1
	Scale efficiency	1.055	1.213	0.879	1.356	1.12575
	Total factor productivity index	1.041	1.165	0.899	1.297	1.1005
Qinzhou	Technical efficiency	1	1	1	1	1
	Technological progress	0.962	0.875	0.91	0.932	0.91975
	Pure technical efficiency	1	1	1	1	1
	Scale efficiency	1	1	1	1	1
	Total factor productivity index	0.962	0.875	0.91	0.932	0.91975

As shown in Table 4, the total factor productivity of waterway transportation in the Beibu Gulf region shows fluctuations in 2016-2020, with an average annual decay of 1% in the Malmquist index, indicating declining waterway transportation technology and management level in Beibu Gulf region. Technical efficiency increases by 3.7% per year and technical progress decays by 3.7% per year. In addition, the comparison reveals consistent variation trend between technological progress index and total factor productivity (TFP) of waterway transportation in the Beibu Gulf region. The attenuation range is very similar, while the technological progress increases in the Malmquist index. In the structure of total factor productivity changes, the mean value of pure technical efficiency basically remains unchanged at 1, indicating that it is impossible to improve output capacity of waterway transportation in the Beibu Gulf simply through resource allocation and utilization. Scale efficiency increases by 3.7% per year, suggesting that the productivity increase of waterway transportation needs to rely on scale.

The Malmquist Index changes are almost synchronized with the technological progress changes, indicating that Malmquist Index is mainly influenced by technological progress. To further analyze the development differences of each city, the Malmquist index is further decomposed as shown in Table 5.

As shown in Table 5, there are different changes in total factor productivity index of waterway transportation in Guangxi Beibu Gulf region in 2016-2020: Fangchenggang and Qinzhou have low total factor productivity index mainly due to the lack of technology, so technological R&D requires more investment. Beihai presents an upward trend in technical efficiency and scale efficiency, with an average increase of 10% in the Malmquist index, which confirms from the side that technical efficiency and scale efficiency improvement affects transportation productivity. Beihai also has insufficient investment in technological progress. In overall, technical advancement of Guangxi Beibu Gulf region waits to be improved.

4. Conclusion

With 1595 km of coastline, the Guangxi Beibu Gulf region is a major waterway transportation corridor to the southwest of China. Relying on waterway assets, it links the upstream and downstream rivers, the left and right coasts, and tributaries. It is necessary to build an economic and social macro system to promote the economic development of the Beibu Gulf region, which is not only a major regional development strategy for China, but also an important link in the 21st Century Maritime Silk Road. The long-term thorough implementation of the “Belt and Road Initiative” is a strategic plan beneficial to China's internal and external linkage development and opening, which also facilitates the coordinated development of coastal, inland and border areas, enhances transportation connectivity, trade facilitation, policy coordination and financial integration. The waterway transportation efficiency in the Guangxi Beibu Gulf region in 2016-2020 is analyzed using DEA model, finding that the main contradiction in the Beibu Gulf region has shifted from shortage of supply and demand to technical efficiency. The results are analyzed as follows.

(1) The overall waterway transportation efficiency in Beibu Gulf is low, and the analysis finds that the low scale efficiency of each city restricts the development of waterway transportation, indicating the need to appropriately increase the scale effect in the construction of waterway transportation, so that waterway transportation resources have greater utilization rate. Total factor productivity index of 2016-2020 has an overall decreasing trend mainly due to the low degree of technological progress. By appropriately increasing investment in science and technology and encouraging technological output, it helps to increase waterway transportation efficiency.

(2) Seen from the input-output slack variables, input-output imbalance exists in the allocation of waterway transportation resources in the Guangxi Beibu Gulf region. After awareness of small number of employees in 2017, Fangchenggang expanded labor scale and reached optimal production efficiency in the following two years. Inefficient use of Beihai labor resources results in capacity redundancy in 2016. Qinzhou has great room for improvement in water transportation scale and uneven production capacity occurs due to blind shrinkage of investment amount. In future development, Beibu Gulf region should reasonably adjust resource allocation, orderly reduce resource input and expand the industry scale to improve the resource utilization effectiveness.

(3) When it comes to waterway transportation efficiency of Beibu Gulf region, technological progress is an important factor influencing total factor productivity. Due to the lack of attention to the construction of waterway transportation technology, slow technological development, backward information technology construction, insufficient platform for high-quality development of waterway transportation, it is impossible to efficiently integrate all links, which seriously impairs the economic circulation. The seaport in the Beibu Gulf region has a late start and a low starting point. It is only in recent years that it starts to support the seaport development, so supporting facilities are incomplete, technological development is relatively slow, and the advantages of seaports are not fully demonstrated. The government needs to increase policy support for waterway transportation and set up programs to encourage the high-tech talent circulation and scientific and technological research.

In addition, sustainability of waterway transportation in the Beibu Gulf region is an important concern in future development. Transportation is the biggest energy consumption mode and pollution source. Considering global climate change and the socio-economic turmoil, it may further affect the watershed change and waterway construction investment. Accordingly, it is necessary to find an integrated approach in future studies by giving consideration to social, economic and ecological impacts on waterway transportation of the watershed.

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