Efficiency Measurement of Logistics Industry in the Yangtze River Delta Region under Low-Carbon Constraints

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Abstract. This study closely combines the characteristics of logistics industry, incorporates energy usage and environmental load to construct an input-output index system for logistics industry. We collect logistics industry data from 2010 to 2022 in the Yangtze River Delta region, including three provinces and one municipality, and use the super-efficiency SBM model with undesirable output to evaluate the efficiency of logistics industry under low-carbon constraints. Findings indicate a W-shaped development trend in the efficiency of the logistics industry in the Yangtze River Delta region under low-carbon constraints. There are significant development differences among the three provinces and one municipality, with Anhui ranking first and Zhejiang ranking last. However, by 2022, the gap between provinces is minimal, indicating a clear trend of integrated and coordinated development. Countermeasures and recommendations are proposed from aspects of comprehensive system construction, technological innovation support and government planning guidance to effectively enhance the efficiency of logistics industry in the Yangtze River Delta region under low-carbon constraints.

Keywords: logistics industry, low-carbon constraints, efficiency measurement, super-efficiency SBM model

1 Introduction

The Yangtze River Delta region has been in a state of rapid economic growth, achieving remarkable achievements since the reform and opening-up. However, it has also led to a substantial increase in carbon emissions. To solve the problem of promoting high-quality economic development and achieving coordinated progress in ecological civilization, the Party Central Committee has prioritized ecological civilization within the overall framework of reform, development and modernization. In 2022, the social logistics value in China surpassed 347.6 trillion yuan, with the logistics industry generating total revenue of 12.7 trillion yuan, equivalent to 10.54% of GDP. Within the Yangtze River Delta region, carbon dioxide emissions from transportation, warehousing, and postal services alone rose from 138.9996 million tons in 2010 to 206.8678 million tons in 2022, displaying an average growth rate of 4.07%. The exceptionally high energy consumption in logistics industry has emerged as a significant contributor to carbon dioxide emissions [1]. Additionally, compared to developed nations, the overall cost of social logistics in the Yangtze River Delta region remains considerably higher, indicating the need for enhanced efficiency and quality in logistics

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operations [2]. It is crucial and urgent to explore ways to improve the efficiency of logistics industry under lower environmental load.

With the increasingly severe global climate change, there is a growing urgency to develop a low-carbon economy. More and more scholars have realized the constraints of resource and paid widespread attention to low-carbon logistics. Research in this field primarily focuses on low-carbon logistics management [3], measurement of logistics carbon emissions [4], and logistics energy efficiency [5]. Within the realm of logistics efficiency, studies emphasize the selection of evaluation indicators [4], [6], model construction [7] and efficiency improvement [8]. The study of evaluation index system mainly follows the economic input-output analysis framework, taking manpower and capital as input and logistics industry output value as output [5]. When it comes to evaluation methods, researchers often adopt methods like Stochastic Frontier Approach(SFA) [9], Data Envelopment Analysis (DEA) [10], Super-Slack-Based Model, and Global Malmquist Index [11].

The current research on logistics industry efficiency has achieved certain results, but there are still some deficiencies. Although many scholars have incorporated environmental resource constraints into logistics industry, few have included energy input and carbon emissions into the total factor productivity framework, making it difficult to accurately reflect the current productivity of logistics industry. Therefore, this study takes into account the low-carbon constraints and focuses on logistics industry in the Yangtze River Delta region. By using super-efficiency SBM model, it measures logistics industry efficiency and analyzes trends, characteristics, and composition of efficiency changes. Finally, this study provides relevant improvement suggestions based on the findings.

2 Model Construction and Data Processing

2.1 Model Construction

SBM model is considered a more scientific method compared to traditional DEA models as it takes into account undesirable output factors. By avoiding deviations caused by radial and angular measurements, it ensures a reflective evaluation of efficiency. In the process of calculating efficiency values, it becomes difficult to make meaningful comparisons when there are repetitive maximum efficiency values equal to 1. In such cases, it is advisable to use super-efficiency analysis to further differentiate those decision-making units (DMUs) with efficiency values of 1, in order to better understand the differences and relative efficiency levels among them. For this reason, this study will use the super-efficiency SBM model [12] for analyze, enabling differentiation and ranking of efficiency values for DMUs. In logistics industry, the efficiency evaluation typically employs a non-oriented model that measures both input and output simultaneously. The specific calculation process is shown in Equation (1).

$$min\rho = \frac{\frac{1}{m}\sum_{i=1}^{m}(\bar{x}/x_{ik})}{\frac{1}{r_1+r_2}\left[\sum_{s=1}^{r_1}\overline{y^d}/y_{sk}^d + \sum_{q=1}^{r_2}\overline{y^u}/y_{qk}^u\right]}$$

$$s.t.\begin{cases} \overline{x} \geq \sum_{j=1,\neq k}^{n} x_{ij}\lambda_j ; \ \overline{y^d} \leq \sum_{j=1,\neq k}^{n} y_{sj}^{d}\lambda_j ; \ \overline{y^u} \geq \sum_{j=1,\neq k}^{n} y_{qj}^{u}\lambda_j \\ \overline{x} \geq x_k ; \ \overline{y^d} \leq y_k^d ; \ \overline{y^u} \geq y_k^u \\ \lambda_j \geq 0 ; \ i = 1,2,\cdots,m ; \ j = 1,2,\cdots,n \\ s = 1,2,\cdots,r_1 ; \ q = 1,2,\cdots,r_2 \end{cases} \quad (1)$$

In Equation (1), ρ denotes the efficiency of logistics industry; m, r_1, r_2 represent the input, desirable output, and undesirable output, respectively, while x , y^d , y^u represent the corresponding matrices; i represents the ith input, s represents the sth desirable output, and q represents the qth undesirable output; j denotes the jth DMU, n is the total number of DMUs, k is the evaluated DMU, and λ signifies the weight.

2.2 Indicator Selection

The logistics industry is experiencing rapid growth, but there is currently no universally accepted classification standard for it, both domestically and internationally. Statistical data indicates that transportation, warehousing, and postal industries make up a substantial portion of the logistics industry, contributing over 85% to its overall value. Scholars have also conducted extensive research on these sectors, suggesting that they provide a representative overview of the logistics industry. Therefore, when establishing an evaluation system for logistics industry under low-carbon constraints, considering its industrial characteristics, development status, energy consumption, and environmental impact is crucial.

The input indicators include the number of employees in logistics industry, average wage of logistics industry employees, financial expenditure, network mileage and energy consumption in logistics industry. The number of employees only reflects the amount of labor input, which only represents a part of labor costs, the average wage of logistics industry employees is used to make up for its deficiency. The network mileage of logistics industry is determined by adding up the railway, highway, and inland waterway mileage. As for energy consumption, it is assessed based on the six energy sources predominantly utilized in the sector: raw coal, gasoline, kerosene, diesel, fuel oil, and natural gas, which are then standardized into a coal equivalent unit.

The desirable output indicators used to assess the logistics industry consist of the added value and the comprehensive turnover of the industry. These indicators respectively represent the economic output and scale output of the industry. The added value serves as a primary indicator to measure the development level. To calculate this, the added values of the transportation, warehousing, and postal sectors are considered as the economic output of logistics industry. Conversely, the comprehensive turnover of logistics industry is a direct indicator of its scale. It is determined by converting both passenger and cargo turnovers into a unified measure, thus representing the overall scale output of logistics industry.

When studying logistics industry efficiency within the framework of low-carbon constraints, a key concern is the negative environmental impact, particularly in terms of carbon dioxide emissions. To analyze and evaluate the industry's efficiency, carbon dioxide emissions are chosen as the undesirable output indicator. To calculate the emissions, the quantities of carbon dioxide produced by the six primary energy sources utilized in the industry are summed, and this computation takes into account the respective conversion coefficients assigned to each energy source.

2.3 Data Sources and Processing

Considering the lag in data publication, this paper selects data from 2010 to 2022. These data cover multiple periods and can reflect various stages of the situation. The primary sources of research data include the annual Statistical Yearbooks of Jiangsu Province, Shanghai Municipality, Zhejiang Province, Anhui Province, and the China Energy Statistical Yearbook. During the data analysis process, it was found that there were missing data for certain years, which were supplemented using the linear interpolation method.

To calculate carbon dioxide emissions, we adopted the IPCC estimation method, as indicated in Equation (2):

$$CO_2 = \sum_{i=1}^{n} E_i \times CF_i \times CC_i \times COF_i \times (44/12) \qquad (2)$$

In Equation (2), i represents different fuel types, E_i represents the consumption of a specific fuel, CF_i represents the average low calorific value of the fuel, CC_i represents the carbon content of the fuel, COF_i represents the oxidation factor of the fuel (with a default value of 1), and (44/12) is the ratio of the molecular weight of carbon dioxide to carbon. $CC_i \times COF_i \times (44/12)$ denotes the effective carbon dioxide emission factor, and $CF_i \times CC_i \times COF_i \times (44/12)$ denotes the carbon dioxide emission coefficient. The correlation coefficients of the six main energy sources are presented in Table 1, indicating their respective relationships to the carbon dioxide emissions.

Table 1: Standard Coal Coefficient and Carbon Dioxide Emission Coefficient of Six Main Fuel

Coefficient Value	Raw coal	Gasoline	Kerosene	Diesel	Fuel Oil	Natural Gas
Standard Coal Coefficient	0.7143	1.4714	1.4714	1.4571	1.4286	1.2150
Carbon Dioxide Emission Coefficient	2.0533	2.9848	3.0795	3.1605	3.2366	1.9963

3 Empirical Analysis

3.1 Evaluation of Logistics Industry Efficiency

Using super-efficiency SBM model with undesirable output, the efficiency of logistics industry in the Yangtze River Delta region of China was assessed while considering low-carbon constraints. MaxDEA 12.1 software was utilized for this purpose. The efficiency values were measured, and the results were used to identify the overall development trend, which is depicted in Figure 1.

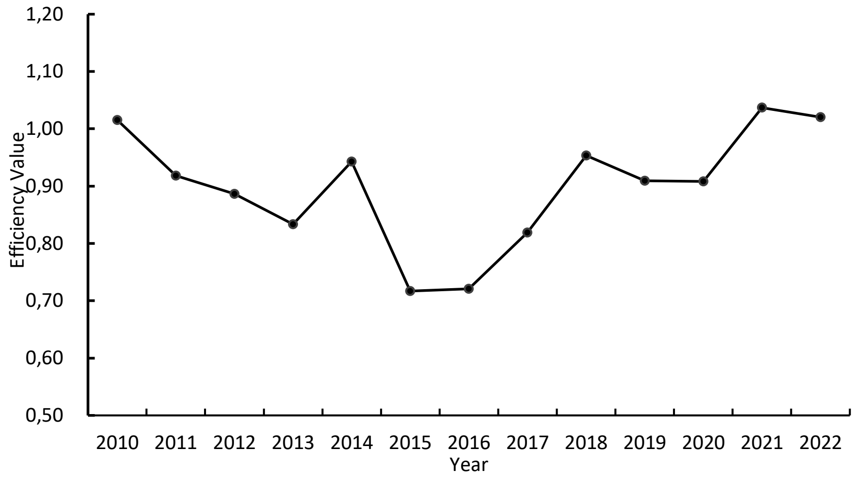

Figure 1: Overall Development Trend of Logistics Industry Efficiency.

The efficiency values presented in Figure 1 demonstrate a W-shaped development trend from 2010 to 2022, reflecting the complex dynamics of logistics industry under the influence of various factors such as major policy adjustments, technological innovation, and market changes. It can be clearly observed that there was a cliff like decline in 2015, with the logistics industry efficiency value dropping from 0.9427 in 2014 to 0.7169 in 2015, representing a 23.95% year-on-year decrease. This was mainly due to the crucial period in 2015-2016 when the Yangtze River Delta region actively carried out transformation and upgrading of low-carbon logistics, which caused short-term adjustment difficulties. In response to climate change, the State Council issued policies aimed at promoting low-carbon logistics, such as the "2014-2015 Action Plan for Energy Conservation, Emission Reduction, and Low Carbon Development", in April 2014. The initial implementation of these policies is often accompanied by short-term adverse factors such as rising costs and operational adjustments, resulting in a temporary decrease in logistics efficiency. Of course, the transformation and upgrading of low-carbon logistics also involves technological updates and switches in various aspects such as transportation vehicles, energy use and information technology. Consequently, logistics enterprises may need to carry out business restructuring, technology upgrading, or even strategic adjustments, leading to a significant but temporary decline in logistics efficiency.

Subsequently, there was a significant improvement in 2017 and 2018, with the efficiency value rapidly rising to 0.9532. This indicates the Yangtze River Delta region overcame initial difficulties and successfully achieved the transition to more sustainable and efficient low-carbon logistics practices. As low-carbon policies were further implemented, enterprises gradually adapted to the policy environment and improving low-carbon logistics efficiency through technological innovation and optimized management. As a result, relevant low-carbon logistics technologies matured and were widely applied, such as electric logistics vehicles and intelligent logistics systems, which greatly improved both logistics efficiency and environmental performance. After experiencing an initial period of adjustment and rapid development, the efficiency remained relatively stable from 2021 to 2022, indicating its transition into a more mature and stable stage of development.

3.2 Comparative Analysis of Logistics Industry Efficiency in the Yangtze River Delta Region

From Table 2 and Figure 2, it is evident that there are notable disparities in the trends of logistics industry efficiency under low-carbon constraints among the three provinces and one municipality from 2010 to 2022. Overall, a descending stepped distribution pattern of "Anhui - Jiangsu - Shanghai - Zhejiang" is observed. Anhui leads with an efficiency value of 0.9426, while Zhejiang lags behind with an efficiency value of 0.8474. Jiangsu and Shanghai have similar efficiency values, occupying the middle segment.

Table 2: Logistics Industry Efficiency Values in the Three Provinces and One Municipality

Year	Shanghai	Jiangsu	Zhejiang	Anhui
2010	1.1730	1.0311	0.7541	1.1036
2011	1.0091	1.0037	0.7924	0.8686
2012	0.8858	1.0157	0.7814	0.8635
2013	0.7119	0.9366	0.7137	0.9711
2014	1.0024	1.0014	0.7389	1.0280
2015	0.6362	0.7392	0.7109	0.7813
2016	0.5869	0.7271	0.7552	0.8138
2017	0.6709	0.8201	0.8913	0.8939
2018	1.0008	0.8365	0.9298	1.0458
2019	0.8482	0.8204	1.0194	0.9493
2020	1.0389	0.8564	0.8755	0.8632
2021	1.0579	1.0163	1.0222	1.0510
2022	1.0113	1.0167	1.0320	1.0204
Mean Value	0.8949	0.9093	0.8474	0.9426

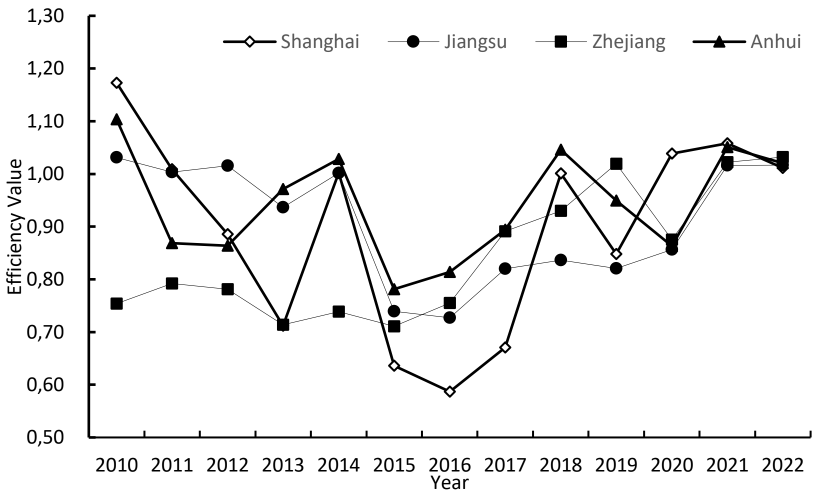

Figure 2: Development Trend of Logistics Industry Efficiency in the Three Provinces and One Municipality.

Upon closer inspection, it is found that the development trend of Zhejiang is quite different from other provinces. Over the research period, the efficiency value of Zhejiang’s logistics industry shows a fluctuating upward trend, climbing from 0.7541 to 1.0320, marking a growth rate of 36.85%. This is attributed to the relatively lagging low-carbon transformation of Zhejiang's logistics industry despite being an economically advanced province. In 2010, the comprehensive turnover level of Zhejiang's logistics industry was significantly lower than that of Shanghai and Anhui, and the added value of the industry was noticeably lower than that of Jiangsu. In the following years, the Zhejiang government strengthened policy support and guidance, including fiscal subsidies, tax incentives, and policy preferences. These measures greatly facilitated logistics enterprises in reducing operating costs and thereby enhancing overall operational efficiency.

On the other hand, Shanghai, Jiangsu, and Anhui experienced a V-shaped development trend, reaching a bottom between 2015 and 2017. This may be attributed to the implementation of a series of measures such as the "Decision of the Central Committee of the Communist Party of China on Some Major Issues Concerning Comprehensively Deepening the Reform”, leading to a rapid decline in logistics industry efficiency in 2015. However, Zhejiang's efficiency value only slightly decreased in 2015 and then started a steady rise. This is because Zhejiang has an advantage in latecomer development, greatly reducing the cost of trial and error, achieving more precise market demand alignment, and driving the logistics industry towards greener and more efficient direction.

By 2022, it can be observed that the difference among the three provinces and one municipality is negligible, with Zhejiang slightly outperforming the others, but the maximum difference is only 0.0207. It is evident that through collaborative development, the level of integration in the Yangtze River Delta region has been consistently bolstered.

4 Conclusions

Utilizing data collected from the logistics industry in three provinces and one municipality in the Yangtze River Delta region of China over the period of 2010 to 2022, the study employs super-efficiency SBM model, which accounts for undesirable outputs, to assess the efficiency of logistics industry under low-carbon constraints. The study reveals a W-shaped development trend in the efficiency values over the study period. In 2015, the industry's efficiency experienced a significant decline, plummeting from 0.9427 in 2014 to 0.7169 in 2015. Subsequently, in 2017 and 2018, the efficiency showed great momentum, rapidly increasing to 0.9532. Following early-stage adjustments and rapid advancements, efficiency levels remained stable from 2021 to 2022. Notably, there were noticeable disparities in efficiency values among the three provinces and one municipality, characterized by a descending stepped distribution pattern: "Anhui - Jiangsu - Shanghai - Zhejiang". By 2022, the divergence in efficiency values among the three provinces and one municipality became negligible, with a maximum difference of only 0.0207, demonstrating a strong trend of integrated and coordinated development. Drawing on these findings, targeted recommendations are suggested to promote higher-level development of logistics industry under low-carbon constraints in the Yangtze River Delta region.

4.1 Promote the Construction of a Comprehensive System

Firstly, optimize the energy system of logistics industry. This involves improving the composition of energy sources used, reducing the reliance on heavily polluting energy sources to minimize carbon dioxide and other pollutant emissions. Secondly, optimize the logistics network layout and scientifically plan the nodes. This involves increasing the construction of low-carbon logistics infrastructure such as rail transportation, further optimizing the layout of logistics transport routes and distribution priorities. At the same time, a scientific approach should be adopted to plan logistics nodes, minimizing energy consumption and promoting low-carbon development at each node. Thirdly, pay attention to the interconnection and organic integration of logistics modes. Scientific selection of transportation modes can effectively reduce energy consumption and improve efficiency. Furthermore, strengthening coordination and cooperative development among various logistics modes can reduce ineffective logistics flow and decrease the proportion of energy consumption. This approach can achieve seamless transfer for passenger transportation and seamless connection for freight transportation, thereby enhancing the overall efficiency of logistics industry.

4.2 Strengthen the Low-carbon Technological Innovation in Logistics Industry

Firstly, promote the adoption and advancement of technology. Accelerate the assimilation and application of cutting-edge technology and management practices to enhance the independent innovation capabilities of logistics companies. Focus on leveraging regional scientific and educational resources, encourage enterprises to establish technology innovation alliances, strengthen research and development in key areas and technologies of low-carbon logistics, and continuously optimize and improve energy-saving and emission-reducing technologies in practical logistics projects. Secondly, emphasize technology promotion and application. Optimize logistics equipment, reduce energy waste, and enable logistics enterprises to transform from traditional to modern models. Furthermore, it is crucial to continue driving the development of information-based logistics systems and providing technical support to advance the low-carbon logistics sector.

4.3 Strengthen the Guidance of Government Planning

Firstly, actively advocate for the concept of low-carbon logistics. Despite ongoing improvements in the infrastructure and transportation capacity of logistics industry in the Yangtze River Delta region, there remains a significant need for further advancements, as many enterprises and consumers having weak understanding of low-carbon logistics. Secondly, strengthen environmental regulations for logistics industry. Government departments should formulate differentiated emission reduction measures, incorporate low-carbon emissions into the standardized analysis variables of logistics industry, and enforce environmental regulations conducive to the sustainable development of the local logistics industry. Continue to streamline the logistics management system between regions and departments, actively promote information infrastructure construction, provide a good platform and carrier for logistics innovation, so as to make the operation of logistics industry more efficient and low-carbon. Thirdly, increase policy support. This can be achieved through measures such as tax incentives, special funds for emission reduction, and financial support. Moreover, the construction of demonstration projects should be emphasized to showcase the leading role of this sector in creating a sustainable future.

In addition, Anhui, Jiangsu, Shanghai, and Zhejiang can take measures according to their characteristics and needs to further enhance the development level of low-carbon logistics industry. As a transportation hub, Anhui can strengthen the construction of transportation infrastructure and improve the supporting facilities and service level of logistics parks. Anhui can also actively promote the use of electric trucks and encourage companies to purchase and use them to reduce carbon emissions from logistics vehicles. Jiangsu, as a major manufacturing province, can leverage its manufacturing advantages to promote the green upgrading of logistics equipment. Investment in research and development of efficient and energy-saving logistics equipment and technologies, such as intelligent warehousing equipment and intelligent logistics distribution systems, can reduce energy consumption and carbon emissions. Shanghai, as an international metropolis, can increase support for multimodal transportation. Encouraging companies to use low-carbon transportation modes such as railways and waterways and optimizing logistics routes can reduce the proportion of road freight. At the same time, Shanghai can actively introduce and promote smart logistics technologies such as the Internet of Things, big data, and artificial intelligence to improve logistics efficiency and reduce empty trips during transportation. Zhejiang is an important area of e-commerce and cross-border trade. It can leverage the power of the Internet and digital technologies to drive the informatization and intelligent development of logistics. Building a unified logistics information platform to facilitate information sharing and interoperability can reduce duplication of labor and resource waste in the logistics process. In addition, Zhejiang can encourage companies to adopt renewable and clean energy sources such as wind and solar energy to reduce carbon emissions in the logistics transportation process. These measures not only help reduce environmental pollution and carbon emissions, but also improve logistics efficiency and reduce logistics costs.

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