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Asssessing the Green Technology Innovation Efficiency in Yangtze River Delta Region under Dual Carbon Background

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Abstract: With the promotion of the dual carbon policy and the process of transforming and upgrading manufacturing, vigorously developing high-tech manufacturing with high-technology content and significant added value has become a powerful driving force to improve the development of the regional economy. In this regard, this research employs the two-stage network SBM-DEA method with undesirable outputs and multi-stage activities involved in the green production process. We examine the green technology innovation efficiency of high-tech manufacturing in the Yangtze River Delta (YRD) region from 2010 to 2020. We divide the activities of the high-tech manufacturing industry into two sub-stages, namely, the research and development (R&D) stage and the result transformation stage. The results are as follows: (1) The efficiency level of green technology innovation in Shanghai is at an outstanding level, having the most significant performance both in the R&D stage at 0.833 as well as in the result transformation stage at 1.006. (2) Anhui's green technology innovation efficiency is mainly driven by the R&D stage. Green technology innovation efficiency in Jiangsu province depends primarily on the stage of result transformation, but there is still room for improvement in resource allocation. (3) Zhejiang needs to catch up in both the R&D stage and the result transformation stage, as well as to optimize the resource allocation of the green technology innovation process.

Keywords: green technology innovation efficiency; SBM-DEA; Yangtze River Delta region; high-tech manufacturing; dual carbon

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1. Introduction

To cope with global climate change, effectively implement the Paris Agreement, and promote a comprehensive green and low-carbon transformation, as well as quality economic development, China proposed the dual carbon concept, including carbon peaking and carbon neutrality, as a major strategic goal in 2020 to accelerate green technology innovation and improve global competitiveness. As the second-largest source of carbon emissions, the traditional extensive development model of manufacturing is no longer sustainable, and high-tech manufacturing is critical for international economic and technological competition. In December 2019, the State Council issued the "Outline of the Yangtze River Delta Regional Integrated Development Plan," claiming that the cooperation of advantageous industries between regions will create an advanced manufacturing base that will be globally competitive and influential. This is an excellent example of how green technology innovation efficiency can be applied to the design of high-quality manufacturing industries elsewhere. Subsequently, in October 2021, the "Opinions of the Central Committee and State Council on the Complete and Accurate Implementation of the New

Development Concept to Achieve Peak Carbon and Carbon Neutrality" were released, aiming to strengthen the green low-carbon development plan to promote carbon-neutral and peak carbon targets, as well as to incorporate dual carbon into the integrated development plan of the YRD region to facilitate the low-carbon transformation of its industries. Green technology also strongly contributes to the realization of the Chinese dual carbon goal. The Chinese government vigorously promotes the development of green technology, and the 13th Five-Year Plan puts forward the five development concepts of "innovation, coordination, green, openness, and sharing," emphasizing that innovation is the first driving force to lead development and green is a necessary condition for sustainable development. With the goal of dual carbon, the high-tech manufacturing industry in the YRD region needs to enhance cooperation and exchange within the region, advance the region's integrated development, and explore the distribution of green technology innovation efficiency and the path of efficiency improvement [1]. In addition to its high added value, the high-tech manufacturing sector provides a solid impetus for achieving the dual carbon objective.

The YRD region is located in the lower reaches of the Chinese Yangtze River. It has a geographical area of about 358,000 square kilometers, accounting for less than 4% of the country's overall area. Approximately 24% of China's GDP came from this region in 2021, with a total GDP of over CNY 27 trillion. Although its geographical area is less than 4% of China, it creates nearly one-quarter of China's total economic output. The main driving force of economic growth in the YRD has been the development of manufacturing industries in the region. The *China Statistical Yearbook* claims that the number of high-tech manufacturing enterprises will reach 12,492 by the end of 2020. The proportion of listed companies in the manufacturing industry in the YRD accounts for 69.45% of all listed companies in the YRD region. Revenue from these companies totals RMB 5020 billion, accounting for 28.75% of the national proportion, making it the largest in China in 2020. As it is located in the lower reaches of the Yangtze River and by the sea, the YRD region is convenient for commerce and transportation. Its geographical advantages make the Yangtze River Delta a manufacturing hub. In addition, the historical development advantage of the YRD region is that the industrial development of the region began very early, and the industrial system is more developed today, which has laid a solid foundation for the modernization of the high-tech manufacturing industry in the YRD region. Academic research has risen to the forefront since China's dual carbon goal was announced. Scholars generally believe that carbon emission-related policies can promote the healthy development of manufacturing industries, as well as the long-term effects of technological innovation on improving manufacturing's international competitiveness [2]. However, there are significant differences in the efficiency of green technology innovation among the YRD regions. In high-tech manufacturing, does the efficiency of various subprocesses impact overall efficiency? To what extent? With the above background analysis and a multi-stage network framework, this study aims to assess and provide a quantitative decision-making basis for technological innovation activities in China's YRD region based on this analysis and industry background.

The research structure of this paper is as follows: Section 2 includes the development status of the high-tech manufacturing industry in the YRD region. In Section 3, we present the data, research methods, and selection of variables. Section 4 applies a two-stage SBM-DEA model to the green technology innovation efficiency of the high-tech manufacturing industry in the YRD region from 2010 to 2020, incorporating overall efficiency, technical efficiency, and transformation efficiency. In Section 4, the description of green technology innovation efficiency is provided over regions. The conclusion and discussion of this paper are presented in Section 5.

2. Literature Review

According to the scholars by Brawn and Wield (1994) [3], green technology innovation was first proposed in the 1970s, which means that by investing in the R&D of green technologies, enterprises can reduce pollution emissions and energy consumption, increase their competitiveness in the market, and in the process of production, operation, and sales, apply green environmental protection patented technologies and green technology fully. With the development of technological research, the difference between green technology and traditional technology is not only whether the green concept is taken into account or not but also the function of reducing resource consumption, improving resource utilization, and reducing environmental pollution [4]. Scholars have been focused on green technology innovation as an essential strategy to promote the industry's high-quality and sustainable development. Guo and Li (2022) [5] applied the network DEA model under the variable returns to scale (VRS) assumption to divide the green technology innovation process of Chinese mining enterprises above designated sizes into two stages: technology development and achievement transformation, along with measures of the efficiency of green technology innovation from 2011 to 2018. In their study on the green technology innovation efficiency of mining enterprises in China from 2011 to 2018, they found that the advancement of technology has a vital role in improving the efficiency of green technology innovation. The DEA-BCC model and Malmquist index were employed by Zhao et al. (2020) [6] to measure the green technology innovation efficiency of each enterprise in the manufacturing industry of Shaanxi Province from 2009 to 2017; their results showed that the enterprises' investment and attention to green technology innovation were crucial to improving their green technology level. Huang and Wang (2021) [7] used the super-efficiency EBM model to calculate and analyze the green innovation efficiency of the manufacturing industry in the Yangtze River region from 2008 to 2019. They found that the differentiation resulting from uncoordinated development within the region affects the level of green technology innovation development in the overall region. Yuan et al. (2019) used a GMM model on the panel data of 30 Chinese provinces to analyze the distribution of green efficiency in China's manufacturing industry technology innovation efficiency [8].

It is evident that internal innovative agents within the territory have major influences on the efficiency of green technology innovation activities since green technology innovation requires a series of processes implemented consecutively [9]. Therefore, measuring efficiency should take into account territorial heterogeneity. Regional differentiation in innovation efficiency can occur due to differences in various characteristics in different regions [10]. It can be explained by strengthening and improving the mechanism of innovation exchange and cooperation between regions. In addition, it can be implemented according to the strengths and weaknesses of each region from the perspective of research methods. Most scholars use the DEA model to evaluate efficiency, and the DEA model has evolved during the research process from a single input-output stage to a two-stage model and then to more stages. In a two-stage DEA model, technology development is divided into R&D and commercial application stages of green technology, which more intuitively illustrates the whole green technology innovation activity and can analyze each stage's problems more precisely [11]. An analysis of the logistics industry conducted by Liu et al. (2021) [12] focuses on enhancing green technology innovation efficiency in the Pearl River Delta region with SBM-DEA in 9 innovative cities in the Pearl River Delta. The result shows that green innovation efficiency fluctuates greatly, so maintaining a stable innovation input and controlling unwanted outcomes are crucial.

As the efficiency of green technology innovation has attracted much attention in academic circles, there are few cases of using the DEA model to study green technology innovation in high-tech manufacturing. In terms of green technology innovation, Lin et al. (2018) [13] evaluated the green technology innovation efficiency of 28 Chinese manufacturing industries between 2006 and 2014. The analysis was carried out using data envelopment analysis (DEA) window analysis with an ideal window width. According to Zeng, Škare, and Lafont (2021) [14], 26 Chinese cities participated in the regional ecological integration of green innovation efficiency in the 5th RD between 2011 and 2017. They both claimed that green technology innovation is essential for the development of manufacturing. They both claimed that green technology innovation is essential for the development of manufacturing. Enterprises need to promote the development of green technology innovation and increase their investment in green technology innovation. Li et al. (2018) [10] explored the efficiency of green technology innovation compared to traditional technology innovation in China's high-end manufacturing industry in the period of 2010–2015, as well as the region-specific heterogeneity with the RAGA-PP-SFA model. In the research by Yang et al. (2022) [15], R&D and achievement transformation are the two stages of green innovation in China's manufacturing industry. In sum, the existing literature on the efficiency estimation of green technology innovation is limited to the high-tech industry in the YRD region. Moreover, prior research on green technology innovation efficiency mainly focuses on the traditional evaluation without considering the internal network structure. Additionally, the negative environmental impact of technology innovation efficiency is not fully considered. Prior studies on green technology innovation efficiency are enumerated in Table 1.

Table 1. Example of studies on green technology innovation efficiency.

Author	Method	Key Findings
Guo et al. (2022) [5]	Network DEA model	Ecological and green growth are primarily benefited from green innovation development.
Zhao et al. (2020) [6]	DEA-BCC model	Innovations in green techniques are essential to improving the enterprises' green technology efficiency values.
Huang et al. (2021) [7]	Super-EBM model	The differentiation resulting from uncoordinated development affects the level of green technology innovation development in the overall region.
Yuan et al. (2019) [8]	GMM model	The manufacturing industry in the central region of China will achieve the transformation and upgrading of the manufacturing industry earlier.
Li et al. (2019) [16]	Network DEA model	Regional differentiation in innovation efficiency can occur due to differences in various characteristics in different regions.
Zhang et al. (2019) [11]	Network DEA model	Enterprises can turn most of their R&D achievements into profits at the commercialization stage.
Liu et al. (2021) [12]	Network DEA model	Maintaining a stable innovation input and controlling unwanted outcomes are crucial for the development of green innovation efficiency.
Lin et al. (2018) [13]	DEA window model	Technological innovation is necessary for enterprises to achieve their development.
Zeng et al. (2021) [14]	Super-SBM model	Enterprises need to increase their investment in the green technology innovation process.
Li et al. (2018) [10]	RAGA-PP-SFA model	High-end manufacturing industries across regions reported a lower value of green technology innovation efficiency than traditional technology innovation efficiency.
Yang et al. (2022) [15]	Three-stage DEA model	Chinese manufacturers have a comparatively low degree of green innovation efficiency.

This paper contributes to the following three segments: first, environmental factors are considered in our research of green technology innovation efficiency in the high-tech manufacturing industry in the YRD region, and the variables of energy consumption and emissions sectors are integrated with the selection of indicators. Secondly, the selection of the research object of green technology innovation efficiency in the YRD region's high-tech manufacturing industry fills the gap in the existing literature on the practical research of green technology innovation efficiency in the YRD region. Finally, this paper selects the two-stage network SBM-DEA model in terms of research methodology. The existing literature on green technology innovation efficiency in the manufacturing industry mainly focuses on single input-output or multi-stage input-output DEA models to examine overall efficiency. The two-stage network SBM-DEA model is an extension of the conventional

DEA model, which takes into account the undesirable outputs and multi-stage activities involved in the "green" production process with a more completed internal structure, which reveals the efficiency of the upstream research and development and downstream result transformation stages.

3. Data and Methodology

3.1. Data

In this paper, we examine the green technology innovation efficiency of the high-tech manufacturing industry in the three provinces of Jiangsu, Zhejiang, and Anhui and one city of Shanghai in the YRD region. The sample data were taken from the *China High-tech Industry Statistical Yearbook*, *China Energy Statistical Yearbook*, and *China Environmental Statistical Yearbook*. Since the *China High-tech Industry Statistical Yearbook* was suspended in 2018, we used the interpolation method for completion. Overall, the final sample selection led to panel data of 44 observations from 2010 to 2020.

3.2. Methodology

The network SBM-DEA model proposed by Tone and Tsutsui (2009) [17] can open the "black box" of the efficiency of an enterprise and divide the process into different sub-stages of efficiency, thereby achieving the distribution of the efficiencies and the condition of overall efficiency affected by the sub-stages (Ma, 2022) [18]. This article considers the two-stage network SBM-DEA model of undesirable output, which takes the external effects of the environment caused by the high-tech manufacturing production process into account. In this structure, the output of the first stage becomes the input in the second stage. These two stages are regarded as independent DMUs, and their efficiency is measured. Considering the goal of dual carbon, it is necessary to assess the impact of undesirable outputs produced by high-tech manufacturing that may have a damaging impact on the environment. Therefore, this paper employs the two-stage network SBM-DEA model used to study the high-tech manufacturing industry in the YRD region.

For each of a set of n DMUs, a conventional description of the process in the literature is as follows: each DMU_J (J = 1, 2, . . . , n) has m inputs X_{ij} (i = 1, 2, . . . , m). This paper divides the DMUs into two stages. The first stage's output is also the second stage's input. The output of the technology development stage and the intermediate variables are denoted as Equation (1):

$$z_j^{(1,2)} = \left[z_{1j}^{(1,2)},\ z_{2j}^{(1,2)}, \cdots, z_{tj}^{(1,2)}\right] \tag{1}$$

Additionally, the intermediate inputs in the conversion stage are listed as Equation (2):

$$x_j^2 = \left(x_{1j}^2,\ x_{2j}^2, \cdots, x_{m_2 j}^2\right) \tag{2}$$

The final production output is denoted as Equation (3):

$$y_j^2 = \left(y_{1j}^2,\ y_{2j}^2, \cdots, y_{rj}^2\right) \tag{3}$$

Then, the possible sets of production in the R&D stage and the result transformation stage are shown in Equations (4) and (5), respectively.

$$T^1 = \begin{cases} \left[x^1, z^{(1,2)}\right] / \sum_{j=1}^n \lambda_j^1 x_{ij}^1 \leq x_{i0}^1, i = 1,\ 2, \cdots, m_1 \\ \sum_{j=1}^n \lambda_j^1 z_{ij}^{(1,2)} \geq z_{t0}^{(1,2)}, t = 1,\ 2, \cdots, T \end{cases} \tag{4}$$

$$T\left[x^1, z^{(1,2)}, y^2\right] = \begin{cases} \left[x^1, z^{(1,2)}, y^2\right] / \sum_{j=1}^n \lambda_j^2 x_{ij}^2 \leq x_{i0}^2,\ i = 1,\ 2, \cdots, m_2 \\ \sum_{j=1}^n \lambda_j^2 z_{ij}^{(1,2)} \leq z_{t0}^{(1,2)}, t = 1, 2, \cdots, T \\ \sum_{j=1}^n \lambda_j^2 y_{rj}^2 \geq y_{r0}^2, r = 1, 2, \cdots, R \end{cases} \tag{5}$$

Therefore, the two-stage network SBM-DEA model for undesirable outputs can be calculated as follows:

$$\rho^{*}=\min\frac{1-\frac{1}{m}\left(\sum_{i=1}^{m}\frac{s_{i}^{-}}{x_{ik}}\right)}{1+\frac{1}{P+Q}\left(\sum_{r=1}^{P}\frac{s_{r}^{g+}}{y_{rk}}+\sum_{q=1}^{Q}\frac{s_{q}^{b+}}{u_{rk}}\right)}$$

$$x_{k}=X\lambda+s^{-} \tag{6}$$

$$y_{k}=Y\lambda+s^{g+}$$

$$u_{k}=U\lambda+s^{b+}$$

$$s^{-},\ s^{g+},\ s^{b+},\ \lambda\geq 0$$

where m, P, and Q represent the number of indicators input, the expected output, and the non-expected output, respectively; λ denotes the strength vector; and s^{-}, s^{g+}, and s^{b+} denote the redundancy of inputs, desired outputs, and undesirable outputs in Equation (6), respectively. When ρ = 1, which means s^{-} = s^{g+} =s^{b+}, there is no redundancy of inputs and non-expected outputs; the evaluated decision unit is effective. When 0 < ρ, the evaluated unit is inefficient, indicating that the number of inputs and outputs needs to be optimized. This paper adopts a two-stage network SBM-DEA model to measure the efficiency of green technology innovation in the YRD region, which is divided into the research and development (R&D) stage and the result transformation stage. The production process of the two-stage network SBM-DEA of high-tech manufacturing and the inputs, outputs, and intermediates are shown in Figure 1.

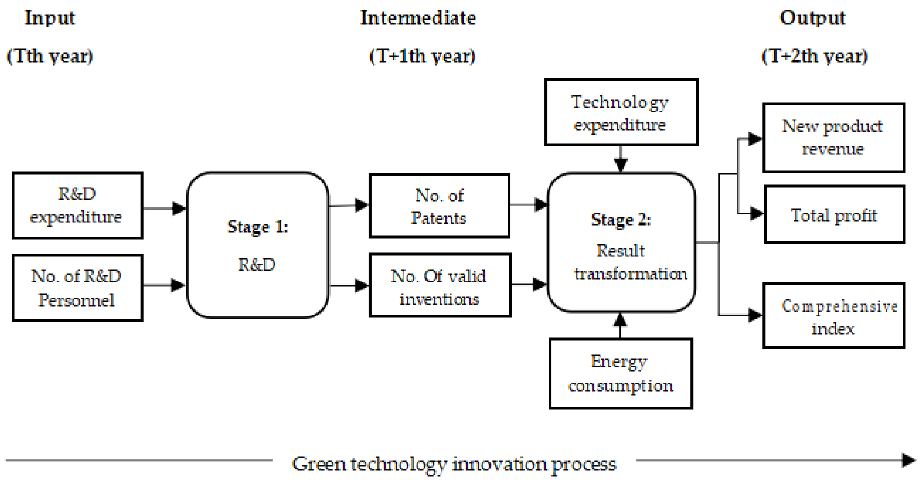

Figure 1. Logic Model of the Production Process of High-tech Manufacturing Industry.

In order to include the most appropriate items for high-tech manufacturing in the efficiency measures of this study, we divided the network two-stage SBM-DEA into the R&D stage and result transformation stage. The input of the R&D stage is defined as: (i) R&D expenditure (X_1) [19] and (ii) no. of R&D personnel (X_2) [20]. The outputs of the R&D stage are also the inputs of the result transformation stage which are listed as: (i) no. of patents (Z_1) [11] and (ii) no. of valid inventions (Z_2) [21]. The non-R&D inputs of the second stage are listed as: (i) technology expenditure (N_1) [22] and (ii) energy consumption (N_2) [12]. The outputs of the second stage are: (i) new product revenue (Y_1) [7] and (ii) total profit (Y_2) [23]; one undesirable output variable is (iii) the comprehensive index of environmental pollution (Y_3) [1]. We generated the overall efficiency (E), R&D efficiency (E1), and the result transformation efficiency (E2). The different variables in the technological innovation process are defined in detail in Table 2. Due to the lag effect of R&D expenditure, this variable adopts the stock index, which is processed by the perpetual inventory method. It applies the R&D value change to the constant price index with 2010 as the base period. For technology expenditure, 2011 is the base period, using the fixed-asset price index to reduce. For the sales revenue of new products, we take 2012 as the base period and use the industrial producer price index to deflate. For New_product, we take 2012 as the base period and use the GDP price index to deflate. Additionally, considering the time lag in the transformation of inputs and outputs, the output indicators are viewed with a one-period lag. As a result, the corresponding years for inputs, intermediate outputs, and outputs are 2010–2018, 2011–2019, and 2012–2020.

Table 2. The Definition of Different Variables of the Green Technology Innovation Process.

Variable	Abbreviation	Explanation
R&D expenditure	R&D_E	The expenditure from the research and development process
No. of patents	Patents	The number of patent applications
No. of valid inventions	Inventions	The number of valid inventions
Technology expenditure	Technology_E	The sum of expenditure for the acquisition of foreign technology, expenditure for the assimilation of technology, expenditure for the purchase of domestic technology, and expenditure for technical renovation
Energy consumption	Energy_C	Consumption of energy
New product revenue	New_product	The revenue gathered from new products
Total profit	Total_Profit	The sum of profits
Comprehensive index of environmental pollution	Pollution_Index	Comprehensive index generated from the result by entropy method on the emissions of "three wastes", including industrial wastewater emissions, industrial sulphur dioxide emissions, and industrial soot emissions
Overall efficiency	E	The value of the efficiency of the whole technological innovation process
R&D efficiency	E_1	The value of efficiency generated from the research and development sub-process
Result transformation efficiency	E_2	The value of efficiency generated from result transformation sub-process

The descriptive statistics of these variables for efficiency measurement are listed in Table 3 below. It can be observed that the mean and standard deviation of each index are used to draw the error bar, which can reflect the degree of dispersion of each figure. As shown in Figure 2, each index has a large dispersion. This indicates that the input and output of green technology innovation activities in the four provinces and cities in the Yangtze River Delta region are significantly different. Prior to calculating efficiency, some additional diagnostic tests were employed on the sample data of this study to identify any potential issues. In this paper, a correlation matrix has been drawn with both Spearman's and Pearson's correlation tests. It can be used to measure the strength of the linear relationship between normally distributed variables. The results in Table 4 show that no high correlation was found among the independent variables of this study.

Table 3. Descriptive Statistics of the Variables for Efficiency Measurement.

Variable			Obs.	Min	Max	Mean	S.D.
Inputs	x1	R&D_E	44	6.020	210.260	61.687	51.625
	x2	Patents	44	6.690	118.290	49.383	36.479
Intermediates	z1	Inventions	44	2.290	40.790	13.380	9.342
	z2	Technology_E	44	0.690	47.540	13.538	11.343
	n1	Energy_C	44	0.700	14.620	4.608	4.333
	n2	New_product	44	105.700	325.260	184.377	78.064
Outputs	y1	Total_Profit	44	38.980	1246.980	363.695	333.427
	y2	Pollution_Index	44	12.090	147.690	52.486	45.159
	y3	R&D_E	44	1.000	216.000	65.600	61.468

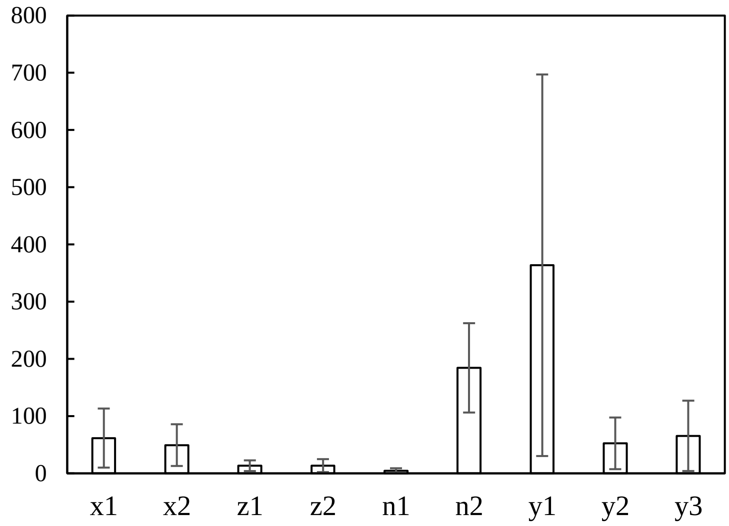

Figure 2. Error Bars of Variables for Efficiency Measurement.

Table 4. Correlation Matrix (Spearman's and Pearson's Correlations).

	x1	x2	z1	z2	n1	n2	y1	y2	y3
x1	1	0.913 **	0.966 **	0.968 **	0.654 **	0.844 **	0.930 **	0.738 **	0.695 **
x2	0.913 **	1	0.954 **	0.818 **	0.798 **	0.962 **	0.959 **	0.866 **	0.852 **
z1	0.966 **	0.954 **	1	0.918 **	0.688 **	0.911 **	0.961 **	0.770 **	0.759 **
z2	0.968 **	0.818 **	0.918 **	1	0.479 **	0.717 **	0.839 **	0.563 **	0.567 **
n1	0.654 **	0.798 **	0.688 **	0.479 **	1	0.889 **	0.814 **	0.968 **	0.872 **
n2	0.844 **	0.962 **	0.911 **	0.717 **	0.889 **	1	0.955 **	0.928 **	0.922 **
y1	0.930 **	0.959 **	0.961 **	0.839 **	0.814 **	0.955 **	1	0.887 **	0.822 **
y2	0.738 **	0.866 **	0.770 **	0.563 **	0.968 **	0.928 **	0.887 **	1	0.860 **
y3	0.695 **	0.852 **	0.759 **	0.567 **	0.872 **	0.922 **	0.822 **	0.860 **	1

Notes: 1. * Significant at the 10% level. ** Significant at the 5% level. 2. Bootstrap results are based on 1000 bootstrap samples.

4. Empirical Analysis

In this study, we measured green innovation efficiency in the Yangtze River Delta region from 2010 to 2020 using MaxDEAultra software and a network SBM-DEA model. In this model, green innovation efficiency can be divided into green innovation efficiency at the overall stage, green innovation efficiency at the R&D stage, and green innovation efficiency at the result transformation stage.

4.1. Preliminary Analysis

As shown in Table 5 and Figure 3, the performance of green technology innovation efficiency in the YRD region changes over time from 2010 to 2020. The regional average values can be compared at different stages of the process from 2010 to 2020. Based on the time dimension and the spatial dimension, we describe the characteristics of green technology innovation efficiency in the Yangtze River Delta region. First, regarding the time dimension, Table 5 demonstrates that the overall efficiency of green technology innovation in the Yangtze River Delta region has fluctuated upward in recent years. During 2010–2011, its green technology innovation efficiency remained around 0.8. In 2014, the green technology innovation efficiency of the company decreased from 0.430 in 2012 to 0.430 in 2014. During 2014 and 2015, the regional green technology innovation efficiency experienced a second wave of growth and remained around 0.85. In 2016, green innovation efficiency dropped to its lowest level in the research period, but from 2017 to 2018, green innovation efficiency increased significantly and reached 0.978. It can be concluded that there is still room for improvement in the efficiency of green technology innovation in the YRD region. In the R&D stage, the efficiency of green technology innovation in the YRD region showed a slow upward trend. Meanwhile, in the result transformation stage, the efficiency of green technology innovation fluctuated upward, which showed a higher average value than that of the overall stage and the R&D stage for each region within the YRD. There is a significant correlation between the fluctuation of green technology innovation efficiency in the YRD region and the result transformation, indicating that in the R&D stage, the improvement of green technology innovation efficiency in the YRD region is limited by achievement transformation, which translates into the ability to transform results into actual industrial products. Second, from a spatial perspective, it can be concluded in Figure 3 that Shanghai has a leading position in the region and is a member of the first echelon of green technology innovation. This can be attributed primarily to its relatively high efficiency in the result transformation stage of green innovation. Research and development efficiency is Anhui's advantage in green technology innovation, which is in the second echelon. Despite the successful transformation in Shanghai and the R&D investment model in Anhui, the efficiency of green technology innovation in Jiangsu and Zhejiang needs to be improved. In addition, the results in Figure 3 show that the provinces that are most efficient in E, E1, and E2 are Shanghai, Anhui, and Shanghai. Combined with geographical location, the R&D efficiency of the high-tech manufacturing industry in the YRD region shows a diagonal distribution characteristic of being high in the west-east and low in the north-south, which is different from the two-adjacent distribution of the efficiency of the overall stage and result transformation stage.

Table 5. Distribution of Different Efficiencies in YRD region.

E	YRD	E2	YRD	E3	YRD
2010–2012	0.795	2010–2011	0.715	2011–2012	0.927
2011–2013	0.859	2011–2012	0.703	2012–2013	1.008
2012–2014	0.511	2012–2013	0.668	2013–2014	0.618
2013–2015	0.430	2013–2014	0.504	2014–2015	0.618
2014–2016	0.894	2014–2015	0.774	2015–2016	1.003
2015–2017	0.847	2015–2016	0.826	2016–2017	0.913
2016–2018	0.353	2016–2017	0.756	2017–2018	0.397
2017–2019	0.643	2017–2018	0.779	2018–2019	0.734
2018–2020	0.978	2018–2019	0.902	2019–2020	1.027
Average	0.701	Average	0.736	Average	0.805

4.2. Distribution Analysis of Green Technology Innovation Efficiency by Region

4.2.1. Overall Efficiency

As illustrated in Table 6, the overall efficiency of green technology innovation in high-tech manufacturing in Jiangsu province is higher than that of Shanghai, Zhejiang, and Anhui provinces in the period from 2011 to 2020, excluding 2010 to 2012. The efficiency value was 0.782 in the period of 2010–2012, but it shows a steady growth trend and reached its maximum value in the period of 2015–2017, maintaining a technology innovation efficiency of one, which indicates that the performance indicator has reached its peak. The growth trend of Shanghai's green technology innovation efficiency appears to be obvious, relatively stable, and less volatile. This indicates that under the dual carbon targets, Shanghai has laid a relatively solid foundation for green technology innovation and is continuously improving its green technology level of innovation. In Anhui, green technology innovation is relatively efficient in most years, but its stability is insufficient from the perspective of change trends over time. Although Anhui has achieved initial results in improving its level of green technology innovation, its path to optimizing and improving it is still immature. Jiangsu and Zhejiang still need to increase investments in research and development and improve resource allocation in green technology innovation.

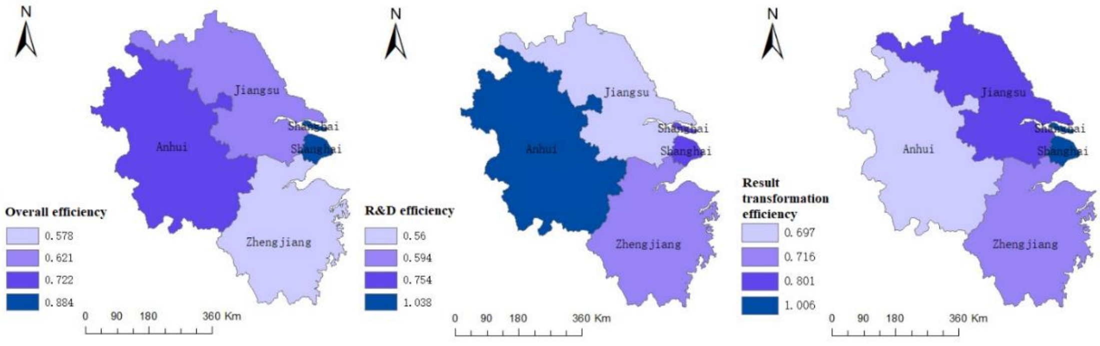

Figure 3. Spatial Distribution of Efficiencies in Each Stage.

Table 6. Distribution of Overall Efficiency in high-tech Manufacturing Industry from 2010 to 2020.

Time Period	Shanghai	Jiangsu	Zhejiang	Anhui	YRD
2010–2012	0.782	0.811	0.587	1.000	0.795
2011–2013	0.805	0.755	0.840	1.036	0.859
2012–2014	0.798	0.183	0.853	0.209	0.511
2013–2015	0.663	0.661	0.163	0.232	0.430
2014–2016	0.891	0.754	0.739	1.193	0.894
2015–2017	1.000	0.771	0.426	1.189	0.847
2016–2018	0.928	0.207	0.156	0.122	0.353
2017–2019	0.912	0.583	0.619	0.459	0.643
2018–2020	1.173	0.863	0.822	1.054	0.978
Average	0.883	0.621	0.578	0.722	0.701

In the YRD region, the green technology innovation efficiency is 0.701, while in Shanghai, Jiangsu, Zhejiang, and Anhui, the green technology innovation efficiency is 0.883, 0.621, 0.587, and 0.722. A regional comparison shows that Shanghai's green technology innovation efficiency is higher than the average value of the Yangtze River Delta region's green technology innovation efficiency. This indicates that Shanghai's green technology innovation efficiency is in the first echelon. Anhui's green technology innovation efficiency is in the second echelon, while Jiangsu and Zhejiang provinces' green technology innovation efficiency is in the third echelon. The advanced science and technology as well as the relatively mature management experience of Anhui and Shanghai should be fully absorbed and utilized by Jiangsu and Zhejiang.

4.2.2. R&D Efficiency

The R&D efficiency of Anhui Province performs better in the second stage, and it performs better than the other three provinces. The results in Table 7 indicate Anhui Province maintained an efficient R&D efficiency from the period of 2010–2019, excluding the years 2012–2013 and 2016–2017. Anhui has an average green technology innovation efficiency of 1.038. This is relatively effective for DEA, and it is in the first echelon, indicating that the high-tech manufacturing industry in Anhui Province invests a lot in technological innovation and attaches great importance to technological research and development and innovation. Shanghai has an average green technology innovation efficiency of 0.754, which is in the second echelon, and the rest of the regions are in the third echelon. It is worth noting that the R&D efficiency in Shanghai is growing rapidly year over year. As of 2019, it reached 1.230. Jiangsu and Zhejiang provinces are third and fourth, with annual averages of 0.560 and 0.594, respectively, below the overall average of 0.736 in the YRD region.

Table 7. Distribution of R&D Efficiency in high-tech Manufacturing Industry from 2010 to 2019.

Time Period	Shanghai	Jiangsu	Zhejiang	Anhui	YRD
2010–2011	0.563	0.623	0.675	1.000	0.715
2011–2012	0.610	0.510	0.680	1.011	0.703
2012–2013	0.596	0.474	0.705	0.898	0.668
2013–2014	0.325	0.322	0.368	1.000	0.504
2014–2015	0.781	0.509	0.617	1.190	0.774
2015–2016	1.000	0.542	0.508	1.252	0.826
2016–2017	0.856	0.627	0.560	0.979	0.756
2017–2018	0.824	0.706	0.587	1.000	0.779
2018–2019	1.230	0.726	0.643	1.008	0.902
Average	0.754	0.560	0.594	1.038	0.736

4.2.3. Rseult Transformation Efficiency

The results in Table 8 show that in the achievement transformation stage, the green technology innovation efficiency of Shanghai reached the relative effectiveness of DEA, and its green innovation efficiency in the first tier was 1.006. This indicates that Shanghai city has been relatively stable and efficient in the transformation of technological results. The high efficiency of Shanghai Province in the result transformation stage makes up for the shortage in the R&D stage. This explains why Shanghai city ranks first in the YRD region in terms of overall efficiency. Jiangsu Province falls into the second echelon, with an innovation efficiency of around 0.8. However, the transformation efficiency of Zhejiang and Anhui Province fluctuated, falling into the third echelon. However, their efficiency performance in the result transformation stage ranges from 0.205 to 1.000 and 0.232 to 10.56, which are great disparities among the sample period, with annual average values of 0.716 and 0.697, which are lower than the overall average value of 0.805.

Table 8. Distribution of Result Transformation Efficiency in high-tech Manufacturing Industry from 2011 to 2020.

Time Period	Shanghai	Jiangsu	Zhejiang	Anhui	YRD
2011–2012	1.000	1.000	0.708	1.000	0.927
2012–2013	1.000	1.000	1.000	1.031	1.008
2013–2014	1.000	0.253	1.000	0.221	0.618
2014–2015	1.000	1.000	0.238	0.232	0.618
2015–2016	1.000	1.000	0.914	1.098	1.003
2016–2017	1.000	1.000	0.598	1.056	0.913
2017–2018	1.000	0.259	0.205	0.124	0.397
2018–2019	1.000	0.695	0.784	0.459	0.734
2019–2020	1.058	1.000	1.000	1.050	1.027
Average	1.006	0.801	0.716	0.697	0.805

It can be observed in Figure 4 that although it shows a trend of improvement in green technology innovation in the YRD region, the development of each region is still unbalanced. In this regard, the efficiency level of green technology innovation in Shanghai is at an outstanding level, showing a two-wheel-drive growth model, both in the R&D stage as well as in the result transformation stage. Anhui's green technology innovation efficiency is mainly driven by the R&D stage. Green technology innovation efficiency in

Jiangsu province depends primarily on the stage of result transformation, but there is still room for improvement in resource allocation. In comparison with other regions, Zhejiang needs to catch up in both the R&D stage and the result transformation stage.

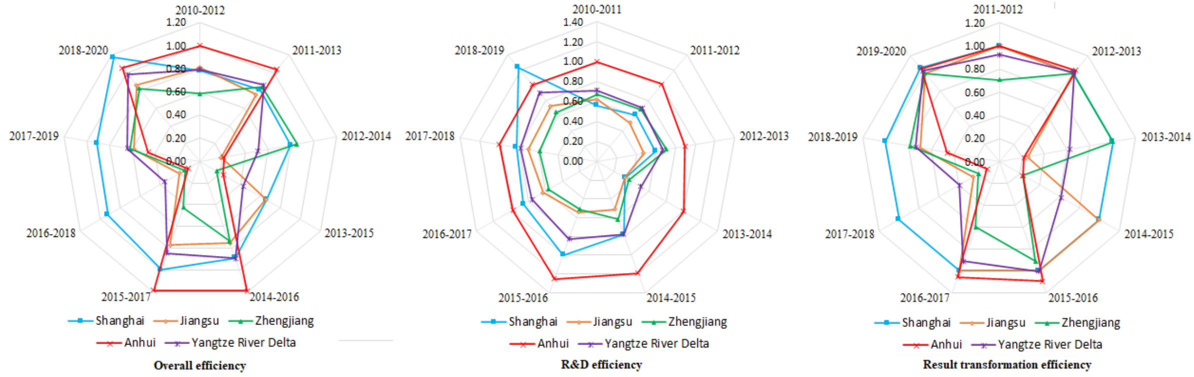

Figure 4. Distribution of the Efficiency by Provinces in YRD region.

5. Discussion and Conclusions

This study has given an account of the technology innovation performance for three provinces and one city in the YRD region, and the efficiency measurement was calculated for assessment during the period 2010–2020 with two-stage network SBM-DEA of an undesirable output. This assignment has explained the distribution of green technology innovation efficiency in two separated stages, namely the R&D stage and the result transformation stage. The findings are as follows. First, the green technology innovation efficiency in the overall stage of the YRD region is not as high as the R&D efficiency and result transformation efficiency, with the average value at 0.701 in this sample period. The overall performance still has a particular gap from the effective frontier. These results imply that the green technology innovation efficiency has not been optimized, and there is an amount of resource waste that is insufficient for achieving the dual carbon goal. Moreover, we found that the green technology efficiency shows a great disparity among the provinces and cities, indicating the uneven development and fierce competition of the manufacturing industry in the YRD region. Finally, regarding the efficiency performance in sub-stages, it was found that Anhui's manufacturing industry is R&D efficient, with an average efficient score of 1.038, but an inefficient performance in the result transformation stage, which means the adequate control of emissions during the process of benefit output is necessary for the Improvement of result transformation of the green technology innovation process. Meanwhile, the average value of result transformation efficiency in Shanghai is relatively better than others at 1.006 between 2011 and 2020. Jiangsu province and Zhejiang province need to further increase R&D investment and improve their resource allocation levels. It is necessary to increase policy and financial support for high-level scientific research talents and research institutions in Jiangsu and Zhejiang provinces and build technology innovation alliances with enterprises, universities, and research institutes. There are limitations to our study. Domestic regulations and socio-economic conditions are crucial for analyzing firm performance [24]. Therefore, our framework needs to be further validated in different social conditions. Additionally, the efficiency performance should be more complete with the various method, improving the schemes to strengthen quantitative evidence.

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