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Research on Green Development Efficiency of Iron and Steel Industry based on Super-Efficient SBM-Malmquist Index Modeling

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Abstract

The green development of the iron and steel industry is not only a new innovative breakthrough for the high-quality development of the iron and steel industry under the “dual-carbon target”, but also an important symbol of the heavy industry's alignment with the construction of ecological civilization. Based on this, this paper takes typical enterprises in China's iron and steel industry as an example, constructs a green development efficiency evaluation system with five levels of capital, labor, energy input, desired and undesired outputs, and measures and evaluates the green development efficiency of the iron and steel industry in the period of 2014-2023 by applying the super-efficient SBM-Malmquist index model. The study shows that:(1) from the level of spatial and temporal evolution, on the one hand, the overall environmental management cost of the iron and steel industry has decreased, and the green development efficiency has shown a rising trend; on the other hand, the green development of the iron and steel industry presents the characteristics of “regional differentiation, technology-driven”, and the overall development trend presents a distribution pattern of North China>Northeast China>East China.(2)From the decomposition results of Malmquist Index, the total factor production of the overall steel industry is growing slowly and steadily, and it is shifting from “efficiency-driven” to “innovation-driven” two-wheel drive mode.

Keywords

Iron and Steel Industry; Dual Carbon Target; Green Development; Super-Efficient SBM-Malmquist Exponential Modeling.

1. Introduction

With the population surge, as well as the improvement of the quality of life of the general public, the iron and steel industry, as an important part of heavy industry, contributes more and more significantly to the GDP growth, and its level of development is also directly related to the overall operation of the national economy and the process of industrialization. As the basic material for infrastructure construction and manufacturing development, its output and quality are important symbols for measuring a country's industrialization level[1]. However, the iron and steel industry generates a large amount of waste and pollutants during the production process, causing serious negative impacts on the environment. Against the background of increasingly severe global environmental problems and resource constraints, the iron and steel industry is facing great challenges. In order to promote green transformation and healthy development, the Chinese government issued the Iron and Steel Industry Development Policy in 2005, the Guidance Opinions on Promoting High-Quality Development of the Iron and Steel Industry in 2022, and the Special Action Plan for Energy

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Saving and Carbon Reduction in the Iron and Steel Industry in 2024, which explicitly put forward the requirements of energy saving and emission reduction and green manufacturing[2].

In order to meet the needs of energy saving and emission reduction and improve resource utilization, traditional technologies have been gradually transformed and developed. Studies have shown that by promoting efficient heat recovery systems and optimizing the use of production processes, energy consumption and waste emissions have been significantly reduced[3]; and by introducing advanced environmentally friendly equipment and materials, some enterprises are expected to achieve the goal of zero emissions[4]. For further in-depth research, this paper will focus on the national, regional, city cluster, provincial and city levels. Based on the national level, Liu Shasha et al. combine the super-efficient SBM with Malmquist-Lenberger index model to measure and analyze the eco-efficiency of five large paper-making countries and give corresponding suggestions for innovation and green development[5];Li Yanige et al. measured the carbon emission efficiency of railroads based on the super-efficient SBM model to verify the validity of regional differences and technological drivers[6]; In the urban agglomeration study, Yang et al. combined the super-efficient SBM model and Malmquist-Luenberger index to measure the efficiency of green economic development in nine coastal provinces in China, and in the direction of green development of China's mariculture industry, proving that technological efficiency and the best-practice gap are the main drivers of the rise in green total factor productivity[7]; Yan et al. used the super-efficient SBM model and the Yan et al. used the super-efficiency SBM model and Malmquist index model to analyze the dynamic changes of energy efficiency under carbon emission constraints in various provinces and cities along the “Belt and Road”[8]. In addition, in order to verify the feasibility of the method, Tian et al. determined the static green innovation efficiency through the super-SBM model, and then used the Malmquist-Luenberger index (ML index) to study the dynamic change of green innovation efficiency and its driving factors, and the analysis showed that the technical efficiency and the change of production technology had a significant impact on the green innovation efficiency[9]; On this basis, Xu et al. followed the model basis of Tone (2001) and constructed a SBM-DEA model considering non-expected outputs, based on inputs and outputs, which effectively solved the slack problem of too much inputs and not enough outputs[10].

In summary, green development efficiency research has made some progress, but there is still great room for improvement in the steel industry. First, the existing research focuses on static efficiency evaluation and pays insufficient attention to dynamic efficiency decomposition and heterogeneity constraints of non-desired outputs. Secondly, the SBM model is mostly used to assess industrial efficiency in China, and the research on green development efficiency in the iron and steel industry needs to be developed urgently. Based on this, this paper innovatively proposes that the super-efficient SBM model is used as a research point to measure efficiency through slack variables, overcoming the defect that the traditional DEA model cannot distinguish efficient decision-making units (DMUs), and combining with the Malmquist-Lenberger (ML) index can dynamically decompose technological progress (TC) and efficiency change (EC). Meanwhile, the representative steel enterprises are used as samples to verify the efficiency trend of green development in the steel industry considering non-desired outputs, and the dynamic evolution process of the steel industry is analyzed based on the ML index.

2. Model and Indicator System Construction

2.1 Super-efficient SBM Model

The traditional SBM model is unable to distinguish DMUs with an efficiency value of 1. The super-efficient SBM accurately measures the relative advantage of efficient units by reconfiguring the production frontier and allowing the efficiency value to exceed 1. The super-efficient SBM model directly quantifies input redundancy and output insufficiency through slack variables to avoid the bias of traditional DEA radial optimization. The model formulation is as follows[11]:

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$$\rho^* = \min \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_{i0}^{-}}{x_{i0}}}{1+\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s^{+}}{y_{r0}}+\sum_{k=1}^{s_2}\frac{s_k^{b}}{b_{k0}}\right)}$$

Constraints:

$$s.t.\begin{cases} x_{i0}=\sum_{j=1}^{n}\lambda_j x_{ij}+s_i^{-}(i=1,2,...,m) \\ y_{r0}=\sum_{j=1}^{n}\lambda_j y_{rj}-s_r^{+}(r=1,2,...,m) \\ \sum_{j=1}^{n}\lambda_j=1 \\ \lambda_j>0, s_i^{-}\geq 0, s_r^{+}\geq 0, s_k^{b}\geq 0 \end{cases}$$

In the expression, x_{ij} is the i-th input of the j-th DMU, y_{rj} is the desired output, and b_{kj} is the undesired output; s_i^{-} , s_r^{+} , and s_k^{b} are the slack variables for input redundancy, undesired output deficiency, and undesired output excess, respectively; λ_j is a vector of weights, and ρ^* is the value of the super-efficiency[12].

2.2 Malmquist Exponential Model

Using the Malmquist index model to reflect the changes in green production efficiency of enterprises from a dynamic perspective ML index is based on the super-efficiency SBM results, which decomposes total factor productivity (TFP) into technical efficiency change (EC) and technical progress (TC) to reveal the driving mechanism of efficiency evolution. The modeling formula for the global covariate is as follows[13]:

$$ML_t^{t+1}=\sqrt{\frac{D^t(x^{t+1},y^{t+1},b^{t+1})}{D^t(x^t,y^t,b^t)}\times\frac{D^{t+1}(x^{t+1},y^{t+1},b^{t+1})}{D^{t+1}(x^t,y^t,b^t)}}$$

Decomposition form:

$$\begin{cases} ML=EC\times TC \\ EC=\frac{D^{t+1}(x^{t+1},y^{t+1},b^{t+1})}{D^t(x^t,y^t,b^t)} \\ TC=\sqrt{\frac{D^t(x^{t+1},y^{t+1},b^{t+1})}{D^{t+1}(x^{t+1},y^{t+1},b^{t+1})}\times\frac{D^t(x^t,y^t,b^t)}{D^{t+1}(x^t,y^t,b^t)}} \end{cases}$$

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In the expression, ML_t^{t+1} is the dynamic change in green total factor productivity from period t to t+1; EC is the change in technical efficiency; TC is the technical progress; x^t is the input vector of period t; y^t is the desired output vector of period t; b^t is the non-desired output vector of period t; $D^t(x^t, y^t, b^t)$ is the distance function of the technological frontier surface of period t, which measures the production efficiency of the decision unit in period t; and $D^t(x^{t+1}, y^{t+1}, b^{t+1})$ is the efficiency level of inputs and outputs in period t, using the period t technological frontier to assess the efficiency level of inputs and outputs in period t+1[14].

2.3 Indicator System Construction

According to the national policy of the Ministry of Industry and Information Technology "iron and steel industry norms and conditions" and the principle of data authority, continuity and availability, reference to the relevant research on the analysis of the current situation of green development of iron and steel enterprises[15], and from the perspective of quantitative analysis of the selected capital, labor, energy inputs, as well as desired and undesired outputs for the indicators reference to the former for the industrial green development efficiency measurement index system[16] to build this paper. Green development efficiency evaluation system. As Table 1.

Table 1. Green development efficiency evaluation system

Indicator type	rating system	Indicator content	Indicator unit
Input Indicator	principal	Actual net investment	billions
		Actual net fixed value	billions
	workforce	Number of enterprise employees	people
	energy	Combined energy consumption per ton of steel	kg of standard coal per ton
		water intensity	Cubic metres per tonne
Output indicator	Expected outputs	Value added of industry	billions
		scientific research	/
	Unexpected outputs	CO_2 emissions from tons of steel	ton
		SO_x emissions from tons of steel	kilogram

3. Example Research and Analysis

3.1 Static Efficiency of Super-efficient SBM Models

This paper will take the data of A, B and C iron and steel enterprises from 2014 to 2023 as an example, covering the three major regions of East China, Northeast China and North China, and apply the green development efficiency evaluation system constructed above to conduct a comprehensive measurement and evaluation as a way to analyze the level of green development of the iron and steel industry, and the required data are obtained from the China Statistical Yearbook as well as the annual reports of the enterprises and the annual report on sustainable development, and the undisclosed data are taken as the Undisclosed data are taken from the average level of the industry at that time. The data collected in this paper are shown in Table 2 (part of the index data of enterprise A).

Based on the established green development efficiency evaluation system, the static efficiency of green development index data of the three enterprises from 2014 to 2023 is measured by adopting the super-efficient SBM model with input-output mixing as the guide, and the empirical results are shown in Table 3.

Table 2. Data on selected indicators for enterprise A

	operation	2014	2015	......	2022	2023
Actual net investment	Enterprise A	182.6	141.59	......	251.1	199
Actual net fixed value		828.97	910.676	......	120.797	1508.341
Number of enterprise employees		134684	126204	......	44445	44445
Combined energy consumption per ton of steel		624	606	......	566.93	563.24
water intensity		4.4	4.2	......	2.39	2.15
Value added of industry		82.78	18.5	......	140.29	137.41
scientific research		939	828	......	1355	1359
CO_2 emissions from tons of steel		3.2	3	......	2.08	2.04
SO_x emissions from tons of steel		0.38	0.3	......	0.265	0.25

Table 3. Green development efficiency results for three firms based on the super-efficient SBM model (2014-2023)

Year	A	B	C
2014	0.529785361	0.346313771	0.533375232
2015	0.279951772	0.57033639	0.400645464
2016	0.587924672	1.159460345	0.63210158
2017	1.077723481	0.588893263	0.747310132
2018	0.96761998	0.725515695	0.861750771
2019	0.736316944	0.980521504	0.870500752
2020	0.762730315	1.137488782	1.311699732
2021	1.186520202	1.342926009	1.420791785
2022	1.550095861	1.226338648	1.25970681
2023	1.075325367	1.022649976	1.244653806
averages	0.875399396	0.910044438	0.928253606

According to the trend of the sample period as shown in Fig. 1, the super-efficiency values of the three representative enterprises of the iron and steel industry all show an overall upward trend, and there is a slight difference between the three enterprises, but there is still a clear convergence. From the super-efficiency SBM values of the three steel representative enterprises, the sample period can be divided into two change intervals: 2014-2019 and 2020-2023. Specific situation analysis: the super-efficiency SBM value of Group A and Group B briefly broke through 1 in 2017 and 2016 respectively, based on the actual analysis, due to the two enterprises enterprise reform and intelligent manufacturing, although it brought a brief efficiency breakthrough, however, from the perspective of the overall efficiency of the calendar year, the efficiency of green development from 2014-2019 is still in a continuous improvement climb; from 2020 for the first time to put forward the After the double carbon target, the steel industry opened the reform, the green development efficiency of the three leading representative enterprises once again broke through 1, and continue to accumulate experience, finally all in 2021 or 2022 green development efficiency reached the highest value.

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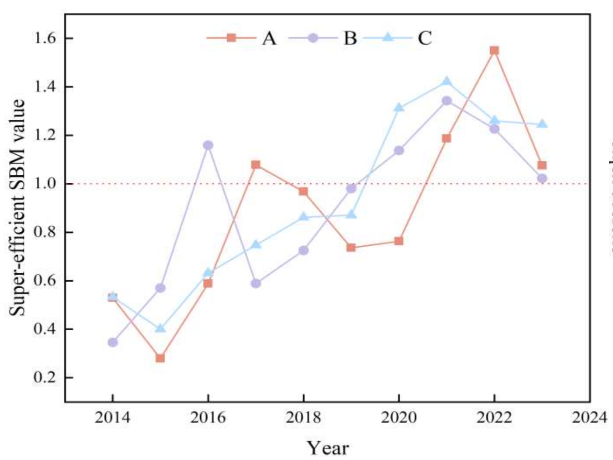

Fig. 1 Variation of super-efficient SBM

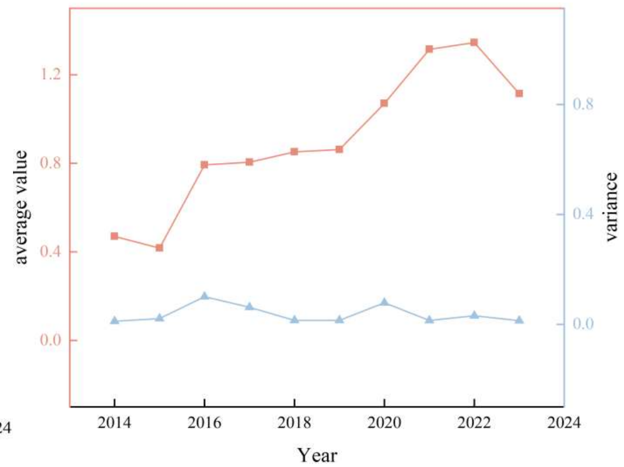

Fig.2 Trends in industry super-efficiency

A, B, C three companies as a representative of the iron and steel industry trends and stability as shown in Fig. 2, ten years of green development efficiency has been steadily improving year by year, fluctuating upward trend, the level of green development is also in a high level of trend, and the trend is very stable, from the point of view of the variance, the steady upward trend is very stable, no substantial increase or decrease.

3.2 Dynamic evolution of the Malmquist index model

Based on the super-efficient SBM model, the ML index is used to measure the dynamic efficiency of the three steel companies from 2014 to 2023, and the results are shown in Table 4.

Table 4. a Enterprise A ML index and its decompositions

Year	A Iron and steel enterprises		
	ML	EC	TC
2014-2015	0.54967	0.84690	0.68751
2015-2016	2.10600	1.44546	1.78056
2016-2017	1.89018	0.86113	2.46060
2017-2018	1.01697	1.05313	0.97812
2018-2019	0.67673	1.23539	0.57888
2019-2020	1.03997	0.95032	1.09414
2020-2021	1.56800	0.87399	2.04254
2021-2022	1.71310	4.24688	0.82857
2022-2023	0.54107	0.71573	0.81098
averages	1.23352	1.35877	1.25132

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Table 4. b Enterprise B ML index and its decompositions

Year	B Iron and steel enterprises		
	ML	EC	TC
2014-2015	1.62489	2.77444	1.20108
2015-2016	2.15443	2.81492	0.86993
2016-2017	0.50886	0.46794	4.17467
2017-2018	0.88038	0.30023	3.23442
2018-2019	0.95740	10.02177	0.17921
2019-2020	3.47025	0.95410	3.58513
2020-2021	1.60191	1.85883	0.91565
2021-2022	0.56455	0.90657	0.73901
2022-2023	0.85131	0.53452	3.72802
averages	1.40155	2.29259	2.06968

Table 4. c Enterprise C ML index and its decompositions

Year	C Iron and steel enterprises		
	ML	EC	TC
2014-2015	1.24779	1.91735	0.61493
2015-2016	1.69606	1.58630	1.05539
2016-2017	1.49588	0.95308	1.56955
2017-2018	1.18568	1.04197	1.13793
2018-2019	0.54859	1.06031	0.50741
2019-2020	2.57848	0.37966	6.09326
2020-2021	1.34489	1.17348	1.17971
2021-2022	0.63187	0.76897	0.81475
2022-2023	0.93802	0.95250	0.98540
averages	1.29636	1.09262	1.55093

According to the data in the above table, the average value of the ML index of the three representative enterprises in the iron and steel industry is greater than 1, which directly indicates that the iron and steel industry's technological efficiency changes under the policy of “dual-carbon target” and the changes in technological efficiency are driving the overall improvement of green total factor productivity (GTFP). Moreover, with the proposal of “dual-carbon target”, the iron and steel industry has gradually shifted from “efficiency-driven” to “innovation-driven” dual-wheel drive mode, which is based on the combination of technological progress (TC) and technological efficiency (EC). (TC) and technical efficiency (EC) synergistic development, two-way drive green total factor productivity progress.

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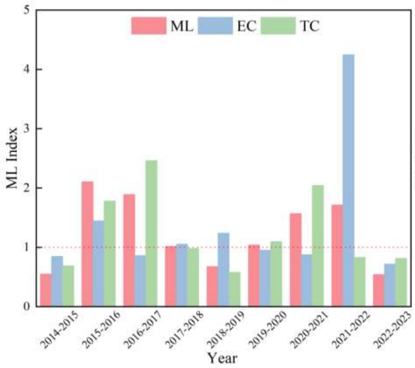

Fig.3 Enterprise A

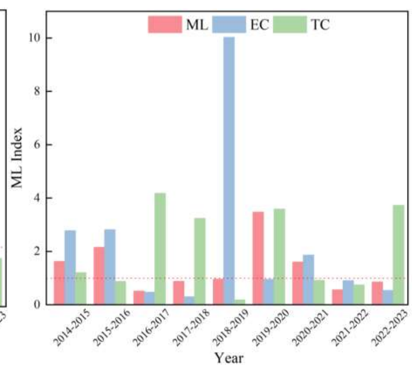

Fig. 4 Enterprise B

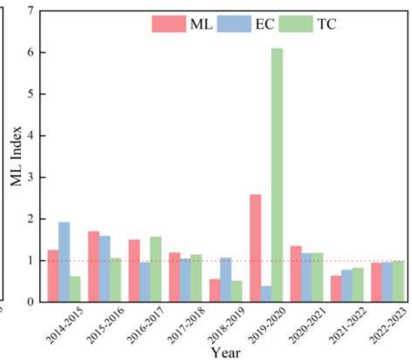

Fig. 5 Enterprise C

As shown in Fig.3(Decomposition of ML index for firm A), from 2014-2016, the ML value of Enterprise A rises from 0.55 to 2.1, and the EC and TC values both rise significantly.Enterprise A attaches importance to green development and actively carries out technological upgrading and efficiency optimization; from 2016-2019, the EC and TC values fluctuate greatly, technological progress encounters a bottleneck, efficiency management is poorly promoted, and the ML value (1.89~0.68) fluctuation declines; in 2019-2023, the EC value and TC value fluctuate significantly, Enterprise A is in a period of deepening transformation, exploring the stable synergistic development of the two;

As shown in Fig.4(Decomposition of ML index for firm B), from 2014-2016, Enterprise B integrated resources, optimized process flow, and significantly improved technical efficiency, although technical progress declined, the ML value still rose from 1.6 to 2.2, and green productivity increased; from 2016-2019, the EC value and TC value fluctuated drastically, and technological innovation did not keep pace with Enterprise B's large-scale structural reforms, and the ML value (0.51~00.96) low and slow rise; 2019-2023 TC value rose significantly, ML value rose in the early period, but the subsequent fluctuations are large, still continue to explore the synergistic development of both technological progress and technical efficiency;

As shown in Fig.5(Decomposition of ML index for firm C), in 2014-2016, Enterprise C's new technology research and development achieved results, technological progress compensated for the decline in technical efficiency, ML value increased from 1.2 to 1.7, green productivity increased; in 2016-2019, EC value was relatively stable, TC value gradually weakened, innovation momentum was insufficient, green productivity declined (1.5~1.19); in 2019-2023, the Initial technical progress is significant, ML = 2.6, green productivity rises sharply, and then falls back, late technical efficiency and technical progress are trying to fluctuate, has initially shown the synergistic development trend of the two.

4. Conclusion and Response

This paper introduces a new research methodology based on the former study, adopting the super-efficient SBM model and Malmquist index model to quantitatively measure the research on the green development efficiency of the iron and steel industry represented by A, B, and C enterprises covering East, Northeast, and North China, and conducts a comprehensive evaluation of the same, and arrives at the following conclusions:

(1) From the spatial and temporal evolution of the green development efficiency of the iron and steel industry represented by these three, temporally, during the period of 2014-2023, the average value of green development efficiency of the iron and steel industry was steadily improved from 0.46 to 1.26, and the overall upward trajectory of low-level oscillation-rapid improvement-collective high efficiency was presented, and the green development transformation of the iron and steel industry has begun to bear fruit; spatially, the green development of the iron and steel industry presents obvious Spatially, the green development of the iron and steel industry shows obvious characteristics of

“regional differentiation, technology-driven”, and the overall development trend shows that North China (0.93) > Northeast China (0.91) > East China (0.88). Overall, the level of green development of the iron and steel industry is steadily moving forward.

(2) From the results of the Malmquist index decomposition of the green development efficiency of the iron and steel industry represented by these three, the total factor productivity change index of the iron and steel industry in 2014-2023 shows a slow upward trend, and it is shifting from “efficiency-driven” to “innovation-driven” dual-wheel drive mode. “In 2015-2016, ML=1.56, EC=1.87, TC=1.03, EC>TC is dominated by technical efficiency; in 2017-2020, ML=1.35, EC=1.61, TC=2.13, TC exceeds EC and is dominated by technological progress; in 2021-2023, ML=1.08, EC=2.13, TC exceeds EC and is dominated by technological progress. ML=1.08, EC=1.337, TC=1.338, EC≈TC as technical progress and technical efficiency are nearly homogeneous and are gradually stabilizing the two-wheel drive and synergistic development.

Based on the above findings, the following response insights can be draw:

(1)Construct a regional coordination mechanism. Construct a compensation mechanism for technology transfer from eastern China to northern and northeastern China, and use emerging green technologies in eastern China to stimulate technological upgrading in northern and northeastern China; and promote a platform for sharing technological resources in northern, northeastern and eastern China to complement each other's advantages in the region.

(2) Implement regional differentiation policies. East China is piloting the emerging carbon emissions trading and encouraging enterprises to participate in international standard-setting; Northeast China is providing tax incentives to guide technological transformation and establishing a cross-regional industrial collaboration mechanism; and North China is increasing the research and development of low-carbon technologies, such as hydrogen energy and short-process steelmaking, and eliminating inefficient production capacity.

(3) Promote the optimization of industrial structure. Strictly carry out the capacity replacement policy of iron and steel enterprises, promote the merger and reorganization of the iron and steel industry, promote the utilization rate of scrap steel in the iron and steel industry, reduce the dependence on primary resources such as iron ore, and promote the coupling development of the iron and steel industry with other related industries, and revitalize the new vitality.

(4) Promote the construction of standard system. The government and steel industry practitioners should speed up the revision and improvement of energy consumption limit standards for the steel industry, low-carbon process technology standards, etc., and establish a sound evaluation system for green products and a quality grading and classification evaluation system.

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