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Measurement of the Green Development Level of China's Manufacturing Industry and Regional Heterogeneity Analysis

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Abstract

In order to enhance the green development level of manufacturing industry and achieve high-quality development of manufacturing industry, this study is based on the input-output data of manufacturing industry in 30 provinces and cities in China from 2012 to 2022. The super efficiency SBM model and GML index are used to measure and analyze the green development level of manufacturing industry in China and the four major economic regions from both static and dynamic perspectives, exploring the overall situation of green development of manufacturing industry and inter provincial and regional differences. The results show that there are significant differences in the green development level of manufacturing industry among provinces, cities, and regions in China from 2012 to 2022; From the perspective of the sources of growth in the level of green development in the manufacturing industry, the driving force for growth mainly relies on advances in green technology; From a regional perspective, the growth rate of green development in China's manufacturing industry is faster in the western and eastern regions than in the central and northeastern regions. Finally, based on the conclusion, suggestions are proposed to enhance the green development level of China's manufacturing industry.

Keywords

Green Development Level of Manufacturing Industry, Super Efficient SBM-GML Model, Regional Differences

1. Introduction

Manufacturing is the foundation and cornerstone of a strong country, and the lifeline of the national economy. At present, China's manufacturing industry is in a critical stage of overcoming difficulties and overcoming obstacles. The 14th Five Year Plan and the 2035 Vision Outline point out: "Adhere to independent controllability, safety and efficiency, promote the upgrading of industrial foundation and modernization of industrial chain, maintain the basic stability of the proportion of manufacturing industry, enhance the competitiveness of manufacturing industry, and promote the high-quality development of manufacturing." This has pointed out the direction for the development of China's manufacturing industry. Green development is increasingly valued by countries worldwide due to its important role in optimizing economic structure. The measurement of green development level in manufacturing industry integrates the concept of green development into the measurement of manufacturing industry level, incorporating energy consumption and environmental factors as inputs and outputs into the evaluation system. It can measure the level of development of China's manufacturing industry, the coordinated development of economy and ecology, and reflect the differences in green development level of China's manufacturing industry in different periods and regional differences in development level between different regions, thus providing reference for the development of China's manufacturing industry. China is the world's largest manufacturing country, with manufacturing added value accounting for about 30% of the global total, ranking first in the world for 14 consecutive years. At the same time, the environmental issues faced by the manufacturing industry cannot be ignored. Many manufacturing processes require a large amount of water resources, such as metallurgy, textiles, and chemical industries. During these processes, many toxic chemicals and waste enter the water body, causing water pollution. This type of water pollution not only disrupts ecological balance, but also affects people's drinking water safety, and there are air pollution, soil pollution, etc., which will seriously affect people's daily lives. China's traditional industries have a large scale, accounting for over 80% of the manufacturing industry. Promoting the transformation and upgrading of traditional manufacturing can not only strengthen green and low-carbon development, improve the ecological environment, but also enable traditional industries to grow new shoots from old trees, further consolidating and enhancing their position and competitiveness in the global industrial division of labor. To ensure the sustained improvement of China's manufacturing competitive advantage, it is necessary to enhance the level of green development in the manufacturing industry, promote the green transformation and upgrading of traditional manufacturing industries, and promote the green and high-quality development of the manufacturing industry.

2. Research Status

Green development of manufacturing industry refers to emphasizing resource conservation, environmental protection, and ecological civilization construction while achieving economic benefits. Through technological innovation and model transformation, it promotes the sustainable, efficient, and environmentally friendly development of manufacturing industry. Zhang Pengwei summarized that the essence of green transformation in the manufacturing industry is to achieve both green and sustainable development goals, as well as the long-term and short-term economic goals of enterprises (Zhang, 2024); Qiao Yue believes that the core of green development in the manufacturing industry is the organic combination of green manufacturing, green industrial chain, and green products. Their common concern is to minimize energy consumption, maximize resource utilization and minimize environmental pollution (Qiao, 2023); Zhang Zeyi pointed out that the green transformation and upgrading of the manufacturing industry is to balance resource intensity and pollution reduction while increasing product added value, promoting the greening and high-end development of the manufacturing industry (Zhang & Cheng, 2023).

At present, there are three main methods for measuring the green development efficiency or green transformation of industries or enterprises: one is the proxy indicator method, where the economic output per unit of environmental pollution comprehensive value (Zeng et al., 2021) and green innovation efficiency (Li & Zeng, 2020) are common proxy indicators for the level of green development; Secondly, based on the connotation of green development, a corresponding indicator system is constructed, and a weighted sum method is used to generate a comprehensive index to comprehensively evaluate and analyze green development. Wang Xiaoling and Han Ping use the entropy method to construct an evaluation index system for green development in the manufacturing industry from four dimensions: economic benefits, innovation drive, energy conservation and environmental regulation (Wang & Han, 2024). Miao Xiaodong and others use subjective weighting methods to quantify the level of green development in the manufacturing industry using three indicators: energy consumption intensity, industrial waste emission intensity, and carbon dioxide emission intensity (Miao et al., 2023). Zhao Bo and Zhong Tianli use principal component analysis to construct an evaluation index system for the transformation and upgrading of the manufacturing industry from three dimensions: economic benefits, independent innovation, and green development (Zhao & Zhong, 2019); Thirdly, the Data Envelopment Analysis (DEA) method is a quantitative analysis method that uses linear programming to evaluate the relative effectiveness of comparable units of the same type based on multiple input and output indicators. It has been widely applied in the study of green development level. For example, Yan Zhiqing and others chose the SBM function based on slack variables, taking capital, labor, and energy consumption as inputs. In terms of output, in addition to GDP, they also considered the emissions of three wastes as unexpected outputs, taking into account multiple dimensions of economy and green (Yan et al., 2024).

The existing research provides reference for the establishment of the indicator system in this study, but there are still some aspects that need improvement: previous studies usually focused on the influencing factors of green development in the manufacturing industry, and paid less attention to the regional differences and causes of green development in the manufacturing industry; At the research methodology level, there is relatively little comparison between green development levels that consider environmental factors and those that do not, and the impact of environmental factors on the green development level of the manufacturing industry is not taken into account. This study incorporates unexpected output into the measurement index system and compares the results of considering unexpected output with those without considering unexpected output, in order to study the regional differences and causes of green development in China's manufacturing industry, propose constructive suggestions for the green transformation of China's manufacturing industry, and achieve high-quality green development of China's manufacturing industry.

3. Data and Methods

3.1. Data Collection

Based on the completeness and availability of data, this article selects manufacturing related data from 30 provinces and cities in China (excluding Xizang, Hong Kong SAR, Macao SAR, and Taiwan Region) from 2012 to 2022 as the research sample. The data on green development in manufacturing industry comes from various sources such as China Statistical Yearbook, China Industrial Statistical Yearbook, China Environmental Statistical Yearbook, China Science and Technology Statistical Yearbook, China Energy Statistical Yearbook, as well as statistical yearbooks and bulletins from the National Bureau of Statistics and various provinces and cities, combined with Wind database and EPS database. For missing data in individual years, linear interpolation is used to supplement to ensure data integrity.

3.2. Super Efficiency SBM Model Including Unexpected Output

The Super Efficiency Slack Based Measure (SBM) model is a commonly used method in academia for measuring the level of green development. This model takes into account slack variables and comprehensively considers the impact of nonlinear relationships between inputs and outputs on the efficiency level of decision units (DMUs). Its advantage lies in not only eliminating non efficiency factors caused by input-output slack, but also effectively handling efficiency evaluation problems that include unexpected outputs (Yao et al., 2024). Compared with traditional DEA (Data Envelopment Analysis) models, the super efficient SBM model breaks through the assumption limitations of output maximization in traditional DEA models, making it more suitable for efficiency measurement scenarios that include unexpected outputs. The super efficient SBM model can significantly improve the accuracy of efficiency measurement results by adjusting the relaxation variables of input-output and non angle selection in a non radial manner, avoiding bias in the calculation. In addition, compared with the original SBM model, the super efficiency SBM model breaks through the limitation of efficiency values being fixed between 0 and 1, thus solving the problem of the original SBM model being unable to sort effective decision units. The efficiency value of the super efficient SBM model can exceed 1, allowing for a more intuitive and accurate comparison of efficiency levels between different decision units. Through this comparative analysis, the non radial and non angular super efficiency SBM model can more accurately reflect the characteristics of efficiency, which helps to clearly distinguish the efficiency differences of decision-making units. Therefore, this study adopts a super efficient SBM model that includes unexpected outputs.

3.3. GML Index Decomposition Model

The super efficient SBM model can measure the static green development efficiency of the manufacturing industry, but it cannot fully reflect the dynamic changes in the green development efficiency of the manufacturing industry. Because the manufacturing industry is subject to various changes in conditions during the long-term production process, these changes can lead to fluctuations in the technological level of the manufacturing industry and affect its green development level. Therefore, when presenting data in panel data format, it is necessary to consider the dynamic situation of development level. In order to solve the problems of linear programming unsolvable and untransferable ML indices in practical applications, Oh (2010) proposed combining the global reference method with the Malmquist Luenberger (ML) index to construct the GML (Global Malmquist Luenberger) index. This index can more effectively reflect the changes in dynamic efficiency.

4. Empirical Analysis

4.1. Static Analysis of the Green Development Level of China's Manufacturing Industry

4.1.1. Analysis of National Static Measurement Results

This article uses the super efficiency SBM model to calculate the green development level of manufacturing industry in various provinces and cities in China from 2012 to 2022 (**Table 1**). From the results, Beijing, Hubei, Tianjin, and Fujian rank among the top four in China, with an average green development efficiency of over 1 for their manufacturing industries, indicating that these provinces and cities are in a leading position in terms of technological level and production scale in green transformation and upgrading. The average efficiency of Jiangxi, Hunan, Shanghai, Guangdong, Shandong, Hebei, Chongqing, Anhui, and Jilin is greater than 0.7, belonging to the second tier in the country. Although its green development level has not reached the forefront, it has performed relatively well. The average efficiency of the remaining 17 provinces and cities is below 0.7, indicating poor overall performance, indicating that these provinces still need to further improve their green development in the manufacturing industry. Among them, Qinghai has the lowest average efficiency and ranks last, reflecting that there is significant room for improvement in its green transformation and upgrading technology and scale efficiency. This distribution reflects the significant differences in green development efficiency of manufacturing industry among regions in China, providing decision-making basis for each region to formulate green development strategies according to local conditions.

Table 1. Green development efficiency values of manufacturing industry in various provinces and cities from.

Provinces and cities	Mean value	Ranking
Beijing	1.536	1
Tianjin	1.027	3
Hebei	0.817	10
Shanghai	0.866	7
Jiangsu	0.641	15
Zhejiang	0.539	18
Fujian	1.021	4
Shandong	0.842	9
Guangdong	0.861	8
Hainan	0.441	21
Shanxi	0.286	29
Anhui	0.745	12
Jiangxi	0.952	5
Henan province	0.693	14
Hubei	1.055	2
Hunan	0.944	6
Inner Mongolia	0.455	19
Guangxi	0.583	17
Chongqing	0.751	11
Sichuan	0.605	16
Guizhou	0.335	27
Yunnan	0.402	23
Shaanxi	0.375	25
Gansu	0.396	24
Qinghai	0.226	30
Ningxia	0.452	20
Xinjiang	0.307	28
Liaoning	0.440	22
Jilin	0.720	13
Heilongjiang	0.375	26

4.1.2. Enhance4.1.2. Analysis of Regional Static Measurement Results

The average efficiency of green development in the manufacturing industry of China's four major economic regions is shown in Table 2, and the corresponding trend chart is shown in Figure 1. It can be found that from 2012 to 2022, the average technical efficiency in the eastern region of China was significantly higher than that in the central, western, and northeastern regions, and was relatively stable. During the sample period, the efficiency remained above 0.75, while the average efficiency in the central region was higher than that in the western and northeastern regions, with stable fluctuations. The average efficiency in the western region showed an overall upward trend year by year, with a good development trend, while the average efficiency in the northeastern region showed an overall downward trend. It can be seen that there are significant regional differences in the green development efficiency of manufacturing in China's four major economic regions, with the eastern region showing better overall performance than the central, western, and northeastern regions.

Table 2. Average green development efficiency of manufacturing industry in China's four major economic regions from 2012 to 2022.

	2012	2013	2014	2015	2016	2017
East	0.957	0.876	0.882	0.901	0.866	0.942
Central section	0.866	0.769	0.770	0.812	0.861	0.850
West	0.401	0.394	0.398	0.394	0.430	0.432
Northeast china	0.681	0.588	0.667	0.591	0.527	0.455
	2018	2019	2020	2021	2022	
East	0.877	0.782	0.766	0.763	0.838	
Central section	0.741	0.678	0.689	0.761	0.771	
West	0.483	0.407	0.412	0.462	0.672	
Northeast China	0.399	0.391	0.406	0.428	0.497	

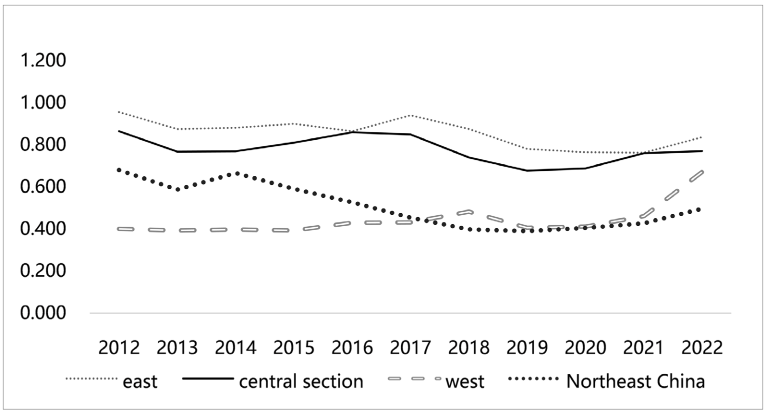

Figure 1. Mean and trend of green development efficiency of manufacturing industry in China's four major economic regions from 2012 to 2022.

4.2. Dynamic Analysis of Green Development Level in China's Manufacturing Industry

4.2.1. Time Dimension Analysis

The changes in the green development level of China's manufacturing industry from 2012 to 2022 are shown in Table 3. From the changes in GML values, the GML index considering unexpected output has an average growth rate of 5.96% in 11 years, while the GML index without unexpected output has an average growth rate of 3.52% in 11 years. Overall, except for a few years, regardless of whether unexpected output is considered, the green development level of manufacturing industry in various provinces and cities in China has increased, moving towards the goal of "resource conservation and environmental friendliness". In addition, the GML index considering unexpected output is higher than that without considering unexpected output, indicating a significant synergistic effect between environmental regulation and manufacturing production efficiency. This empirical result not only verifies the promoting effect of environmental regulation on the green transformation of manufacturing industry, but also provides strong evidence for Porter's hypothesis, indicating that appropriate environmental regulation policies can achieve a "win-win" result between environmental protection and industrial development.

Table 3. Annual GML index changes and decomposition of China's manufacturing industry from 2012 to 2022.

	Not considering unexpected outputs			Consider unexpected outputs		
Year	GML index	GEC index	GTC index	GML index	GEC index	GTC index
2012-2013	1.0174	0.9589	1.0699	1.0245	0.9396	1.1011
2013-2014	1.0341	0.9911	1.0437	1.0396	0.9970	1.0493
2014-2015	0.9909	0.9804	1.0154	0.9875	0.9895	1.0035
2015-2016	1.0374	0.9835	1.0613	1.0909	1.0315	1.0647
2016-2017	1.0128	1.0425	0.9782	1.0244	1.0622	0.9803
2017-2018	1.0197	1.0244	1.0167	1.0210	1.0265	1.0541
2018-2019	1.0433	0.9440	1.1197	1.0571	0.9312	1.1711
2019-2020	0.9873	1.0219	0.9662	1.0157	1.0070	1.0103
2020-2021	1.2184	1.0532	1.1586	1.3436	1.0787	1.2545
2021-2022	0.9906	1.2030	0.8226	0.9921	1.2365	0.8202
mean value	1.0352	1.0203	1.0252	1.0596	1.0300	1.0509
Average growth rate	3.52%	2.03%	2.52%	5.96%	3.00%	5.09%

From the perspective of temporal trends, the GML index of green development in China's manufacturing industry was 1.0245 and 1.0396 in 2012 and 2013, respectively, with growth rates of 2.45% and 3.96%. However, the GML index for green development in the manufacturing industry plummeted by 1.25% in 2014. 2015 was a turning point, and since then, the level of green development in China's manufacturing industry has shown a steady upward trend. This is partly because since the establishment of the new development concept at the Fifth Plenary Session of the 18th Central Committee of the Communist Party of China in 2015, China's traditional manufacturing industry has embarked on a systematic and in-depth green transformation process, effectively promoting the green upgrading of industrial structure and moving towards the path of high-quality and sustainable development. In 2020, the GML index showed a significant increase, which was mainly due to the interruption of the global supply chain caused by the COVID-19 epidemic in 2020. In the short term, the capacity utilization rate of China's manufacturing industry declined, and some high energy consuming and high emission industries (such as steel and chemical industry) passively reduced production, significantly reducing pollutant emissions. In the process of resuming production, the government guided enterprises to give priority to resuming cleaner production processes through policies, promoting energy efficiency optimization, and improving green production efficiency in the short term. The significant decline in 2021 is due to the rapid expansion of manufacturing capacity driven by the global economic recovery from the second half of 2021 to 2022. Some industries (such as coal and chemical) increased production to compensate for the losses caused by the epidemic, leading to a rebound in energy consumption and carbon emissions. From the decomposition of the index, the GEC value (change in green technology efficiency) with an average annual growth rate of 3.00% is lower than the GTC value (change in green technology progress) with an average annual growth rate of 5.09%. Compared with the improvement of green technology efficiency, technological progress is the main reason for the increase in GML value.

4.2.2. Spatial Dimension Analysis

Table 4 shows the GML index and its decomposition values for green development of manufacturing industry in different provinces and cities in China. Taking into account unexpected output, the provinces and cities with relatively high GML index mean values from 2012 to 2022 are Ningxia, Hebei, Beijing, and Yunnan, with growth rates of 20.48%, 12.39%, 10.75%, and 10.6%, respectively. Provinces such as Shandong (−1.04%), Jilin (0.21%), Anhui (0.67%), and Henan (0.93%) have relatively stagnant growth rates, highlighting the uneven regional development characteristics. It is worth noting that, except for Shandong, the GML index of all other provinces is greater than 1, indicating an overall upward trend in the green development level of the manufacturing industry. Further decomposition of the GML index revealed that there were 28 provinces and cities with GTC values (changes in green technology progress) greater than 1, while only 22 provinces and cities with GEC values (changes in green technology efficiency) greater than 1. This also proves that China's manufacturing industry achieved GML value growth more through technological progress during the sample period.

Table 4. GML index and its decomposition mean of green development of manufacturing industry by provinces and cities in China.

Region	Provinces and cities	Not considering unexpected outputs			Consider unexpected outputs		
		GML index	GEC index	GTC index	GML index	GEC index	GTC index
Eastern region	Beijing	1.0571	1.0284	1.0490	1.1075	1.0038	1.1194
	Tianjin	1.0290	1.0053	1.0283	1.0893	1.0086	1.0863
	Hebei	1.0588	1.0334	1.0374	1.1239	1.0740	1.0786
	Shanghai	1.0364	1.0147	1.0264	1.0557	1.0155	1.0662
	Jiangsu	0.9923	0.9598	1.0609	1.0269	0.9579	1.0964
	Zhejiang	1.0358	1.0157	1.0248	1.0612	1.0119	1.0536
	Fujian	1.0433	1.0052	1.0436	1.0841	1.0066	1.0818
	Shandong	0.9876	0.9770	1.0176	0.9896	0.9561	1.0565
	Guangdong	1.0178	0.9977	1.0264	1.0534	1.0195	1.0690
	Hainan	1.0303	1.0153	1.0226	1.0450	1.0122	1.0398
	average	1.0288	1.0052	1.0337	1.0637	1.0066	1.0748
Central region	Shanxi	1.0646	1.0527	1.0163	1.0705	1.0552	1.0198
	Anhui	0.9925	0.9678	1.0328	1.0067	0.9531	1.0823
	Jiangxi	1.0046	0.9988	1.0071	1.0342	1.0102	1.0272
	Henan province	0.9936	0.9699	1.0247	1.0093	0.9497	1.0697
	Hubei	1.0301	1.0028	1.0293	1.0601	1.0024	1.0568
	Hunan	1.0242	1.0161	1.0155	1.0722	1.0337	1.0411
	average	1.0182	1.0013	1.0209	1.0422	1.0007	1.0495
Western Region	Inner Mongolia	1.0639	1.0608	1.0097	1.0847	1.1164	0.9979
	Guangxi	1.0197	1.0009	1.0218	1.0298	1.0025	1.0333
	Chongqing	1.0440	1.0262	1.0221	1.0880	1.0532	1.0384
	Sichuan	1.0207	0.9976	1.0246	1.0362	0.9908	1.0478
	Guizhou	1.0430	1.0341	1.0120	1.0477	1.0331	1.0189
	Yunnan	1.0885	1.1134	0.9979	1.1060	1.1811	0.9888
	Shaanxi	1.0471	1.0362	1.0179	1.0637	1.0436	1.0264
	Gansu Province	1.0261	1.0139	1.0190	1.0347	1.0189	1.0221
	Qinghai	1.0864	1.0768	1.0147	1.0898	1.0796	1.0155
	Ningxia	1.1401	1.1634	1.0791	1.2048	1.3035	1.1433
	Xinjiang	1.0501	1.0394	1.0156	1.0593	1.0459	1.0178
	average	1.0572	1.0511	1.0213	1.0768	1.0790	1.0318

Continued

the Northeast	Liaoning	1.0031	0.9919	1.0201	1.0114	0.9833	1.0360
	Jilin	0.9915	0.9742	1.0231	1.0021	0.9594	1.0700
	Heilongjiang	1.0334	1.0192	1.0172	1.0415	1.0170	1.0263
	average	1.0093	0.9951	1.0201	1.0183	0.9866	1.0441
National average		1.0352	1.0203	1.0252	1.0596	1.0300	1.0509

From a regional perspective, taking into account unexpected output, the average GML indices for the eastern, central, western, and northeastern regions of China from 2012 to 2020 were 1.0637, 1.0422, 1.0768, and 1.0183, respectively. The reason for the fastest growth rate in the western region is that the manufacturing foundation in the western region is weak, and it can directly skip the traditional extensive stage and adopt the latest green technologies. In addition, clean energy is abundant (the western region has more than 80% of the country's wind and solar energy resources). Therefore, in the context of green transformation of the manufacturing industry, although the static efficiency level in the western region is lower than that in the eastern region, its growth rate is higher than that in the eastern region. As an old industrial base in China, the Northeast region has a large number of traditional manufacturing industries, and the process of green transformation and upgrading is relatively slow. However, although its growth rate is slow, only 1.495%, it is still growing positively. It should be recognized that the transformation and upgrading of the manufacturing industry in Northeast China is a complex and lengthy process that requires efforts from the government, enterprises, and society.

By comparing the GML index without considering unexpected output, it can be found that the GML index with considering unexpected output is higher than that without considering unexpected output nationwide, as well as in the eastern, central, western, and northeastern regions. This phenomenon indicates that during this period, environmental regulatory policies have had a significant promoting effect on the green transformation of the manufacturing industry, which is mainly achieved through two mechanisms: one is the "innovation compensation effect", where environmental regulations force enterprises to engage in green technology innovation, driving the improvement of the Technology Progress Index (GTC); The second is the "efficiency improvement effect", which improves the technical efficiency index (GEC) by optimizing resource allocation and management models. From the decomposition of the index, it can be seen that the GEC index and GTC index considering unexpected output are higher than those not considering unexpected output, which also confirms this point.

5. Conclusion

This study used the super efficient SBM model and GML index to conduct static and dynamic analysis of the green development level of manufacturing industry in 30 provinces and cities in China from 2012 to 2022. The main conclusions are as follows: 1) From the static measurement results of the green development level of China's manufacturing industry, it can be seen that 17 out of 30 provinces and cities had an average efficiency below 0.7 during the research period, indicating that there is still significant room for improvement in China's manufacturing industry in terms of green transformation and upgrading. From a regional perspective, there are significant regional differences in the green development efficiency of manufacturing in China's four major economic regions, with the eastern region showing better overall performance than the central, western, and northeastern regions. 2) From the dynamic measurement results of the green development level of China's manufacturing industry, it can be seen that the GML index considering unexpected output has an average growth rate of 5.96% in 11 years during the research period, while the GML index without unexpected output has an average growth rate of 3.52% in 11 years. After considering the correction of unexpected output, the GML index has actually increased, indicating that appropriate environmental regulations can achieve a "win-win" result between environmental protection and industrial development. From the decomposition of the index, the GTC value (changes in green technology progress) and GEC value (changes in green technology efficiency) also prove this point. From the perspective of various provinces and cities, considering unexpected output, except for Shandong where the GML index is less than 1, the GML indices of other provinces and cities are all greater than 1, indicating an overall upward trend in the green development level of the manufacturing industry; From the perspective of the sources of growth in the level of green development in the manufacturing industry, the driving force for growth mainly relies on advances in green technology; From a regional perspective, the growth rate of green development in China's manufacturing industry is faster in the western and eastern regions than in the central and northeastern regions. The majority of traditional manufacturing industries in Northeast China have a slower process of green transformation and upgrading.

6. Suggestions

Based on the above conclusions, this study proposes the following suggestions: firstly, pay attention to regional differences and promote coordinated regional development. There is a significant imbalance in the green development level of China's manufacturing industry between provinces and regions, with higher quality in the eastern region. To promote coordinated development, each region needs to formulate policies tailored to local conditions, leverage advantages, and enhance the level of green development. The government should increase public investment, support the upgrading of the manufacturing industry, promote the landing of high-tech industries, promote technological innovation and energy conservation and emission reduction [13]. The central and western regions as well as the northeastern region have begun to adjust the direction of scale investment, and should pay more attention to investment in technological level, actively promote scientific and technological innovation and upgrading, in order to improve the efficiency and quality of green development in the manufacturing industry, rather than just focusing on manpower and capital investment. In addition, it is necessary to guide green consumption in society, enhance environmental awareness, promote the production of low-carbon products by enterprises, improve environmental quality, and achieve an increase in the level of green development in the manufacturing industry.

Secondly, we attach great importance to technological innovation while improving technological efficiency. Technological innovation is the fundamental basis for enterprises to establish themselves in the market, and it is also the key guarantee for mastering market discourse power and dominant position. The manufacturing industry urgently needs to increase investment in technological innovation and continuously strengthen technological accumulation. By increasing research and development investment, optimizing innovation mechanisms, introducing high-end talents, deepening industry university research cooperation, promoting breakthroughs and applications of key technologies, and comprehensively improving the industry's technological level. Only by continuously promoting technological innovation and accumulation can we break through existing technological bottlenecks, achieve a transition from scale expansion to quality improvement, and ultimately move towards high-quality development. At the same time, attention should also be paid to improving technical efficiency through measures such as optimizing factor allocation and improving management systems. Currently, some provinces tend to prioritize technology over efficiency, which to some extent restricts the improvement of green development level. Only by achieving the coordinated development of technological progress and efficiency improvement can we ensure the quality and efficiency of the green transformation of the manufacturing industry, and promote the formation of a new pattern of regional coordinated development.

Thirdly, implement the new development concept and plan environmental regulatory measures reasonably. The green transformation of manufacturing industries in various regions is led and controlled by the government, which plays an indispensable role. By balancing the intensity of environmental regulations, the government can encourage enterprises to embark on a green development path that saves resources and reduces pollution. To effectively achieve the dual benefits of environmental regulation on economic growth and ecological protection, there is still great room for improvement in the formulation and implementation of relevant policies at this stage. For example, when choosing regulatory tools, the market should play a guiding role, promote the use of incentive and voluntary regulatory measures, inject innovative vitality into traditional command based regulation, encourage enterprises to actively integrate into the green development framework, and help the government's environmental governance effectiveness while improving their total factor productivity. In order to ensure the effective implementation of environmental regulatory policies, the government needs to take supporting measures, including improving the environmental legislation system, clarifying environmental property rights, and strengthening legal support; Establish a sound environmental performance evaluation mechanism and regulatory tool effectiveness evaluation system, use experts and scientific testing methods to evaluate regulated enterprises, and timely release results to commend outstanding enterprises and effective tools; At the same time, a flexible supervision mechanism should be established to comprehensively regulate the environmental behavior of enterprises in conjunction with public participation. Through the above safeguard measures, we will promote environmental regulations to play a more significant role in improving the green development level of the manufacturing industry.

7. Model Limitations

While the Super-Efficiency SBM model and GML index offer significant advantages for measuring green efficiency and its dynamics (e.g., effectively handling undesirable outputs, allowing efficiency scores > 1 for ranking, avoiding infeasible linear programming solutions), their application to analyzing the regional heterogeneity of green development in China's manufacturing sector necessitates a critical consideration of limitations within the context of China's complex and differentiated regional industrial policies:

Although the GML index captures dynamic changes over time, it fundamentally calculates relative efficiency based on observed input-output data. The models themselves cannot endogenously capture or isolate the direct impact of specific regional policy interventions (e.g., targeted fiscal subsidies, central environmental inspections, specific industry access restrictions, regional carbon emission trading pilots) on efficiency changes. For example, during the study period (2012-2022), China's environmental regulations significantly strengthened (e.g., "Air Ten Points," "Water Ten Points," "Dual Carbon" goals), and enforcement intensity and supporting measures likely varied across regions. These exogenous, non-market-based, strong policy shocks could significantly influence efficiency scores (notably short-term fluctuations, like the sharp rise in 2020 in **Table 4**), but the models inherently struggle to quantitatively disentangle this policy effect from market-driven efficiency changes (e.g., technological progress GTC, management improvement GEC).

Therefore, while leveraging the power of these models, the interpretation of our empirical findings (significant inter-provincial/regional disparities, the dominant role of technological progress, faster growth in the West, etc.) should be contextualized within a deep understanding of China's uneven regional development and differentiated industrial policy landscape. Future research could explore constructing group frontiers for regions, incorporating proxy variables for regional policy intensity, or adopting more sophisticated modeling frameworks better suited to heterogeneity and policy shocks to provide a more nuanced picture of China's manufacturing green transition under complex regional policy environments.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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