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Green Growth or Gray Growth: Measuring Green Growth Efficiency of the Manufacturing Industry in China

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Abstract: The manufacturing industry has created a rapid evolution of the economy, but it has also negatively impacted the ecosystem. A better understanding of the manufacturing industry in green growth is crucial to achieving the sustainability goals in China's high-quality development stage and is better for identifying the impact of scale effect or technological effect in EKC. In this research, a super-efficiency slacks-based measure model is proposed to evaluate the green growth efficiency of 27 manufacturing industries, and a Luenberger index method is adopted to interpret the driving forces of efficiency. The results demonstrate that green growth efficiency in the manufacturing industry shows a fluctuating upward trend, and more than 60% of the industries are in a gray growth state. The growth of green growth efficiency mainly depends on the pulling effect of technological dividends brought by technological progress, rather than the improvement of technical efficiency. As the industry heterogeneity is analyzed, technology-intensive industries still dominate in the process of manufacturing industry and have shown a significant upward trend. Finally, some suggestions are proposed from the perspective of the government and enterprises.

Keywords: manufacturing industry; green growth; efficiency

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1. Introduction

Manufacturing enterprises have made great achievements in realizing industrialization, but they are still unable to eliminate the "3 H" problems: high investment, high export, and high energy consumption [1]. According to the statistics of the World Bank, the added value of China's manufacturing industry in 2019 was close to $4 trillion, ranking first in the world. With a manufacturing added value of nearly $2.3 trillion, the United States comes in second, comparable to 57.5% of China's manufacturing scale. [2]. China's manufacturing capacity, however, continues to lag behind that of developed economies in general. The growth rate of added value in China's manufacturing industry has consistently been around 20% from 2012 to 2019, which is much lower than the high level of more than 30% in the US and Germany for a long period. There are growth traps of low-end overcapacity and high-end overcapacity to varying degrees [3]. The enormous gap has made it clear how China's manufacturing industry is currently under strain. The non-green expansion of the manufacturing industry has consumed a lot of natural resources and accelerated the deterioration of the ecological environment for a long time [4]. The term "green manufacturing" was initially introduced in 1996 by the American Society of Manufacturing Engineers, and then the global advanced manufacturing sector started embracing "green" [5]. The negative pressure on China's economic development is still significant due to COVID-19, as seen by the manufacturing sector's slow recovery, the continued fall in direct investment, and the potential for further rises in trade uncertainty [6]. A critical issue for China's manufacturing development is resolving the tension between the economy and the environment and harmonizing the conflict between "green" and "growing" [7]. It has become harder and harder to sustain economic growth by making significant increases in energy, capital, and other investments. Along with three layers of changes in industrial structure, growth impetus, and growth state, the manufacturing industry is beginning to transition from gray and black growth to green growth [8]. Promoting green growth requires a deeper understanding of the manufacturing industry's level of greening, as well as the identification of its growth condition and analysis of its development drivers.

Compared to traditional economic growth theories, green growth theory emphasizes both the outcomes of the convergence of production elements, such as labor, material, technology, and human resources, as well as the significant influence of the environment as a new factor [9]. According to the "decoupling theory", green growth is the actual decoupling of the economy from resource use and environmental devastation while attaining economic growth and increases in social welfare. Theoretical debate on the correlation between environmental quality and wealth has grown since the environmental Kuznets curve (EKC) was proposed [10]. Grossman and Krueger identified three mechanisms via which economic growth could influence environmental quality: scale effects, technological effects, and structural effects. Decoupling the economy from the environment and the use of resources is a key component of green growth [11]. By examining green growth efficiency for dynamic efficiency dismantling, we can ascertain whether the scale effect or technology impact is to blame for the improvement in green growth efficiency and further develop the theoretical justification for EKC.

The efficiency of green growth serves as the foundation for the examination of its level, and recent popular topics have included index selection, assessment systems, measuring tools, and techniques [12]. The conventional approach of measuring the green growth of the manufacturing industry by a single indicator has some limitations. In order to evaluate the progress of this process of development in light of the effects of undesirable output (such as air pollution and water pollution on green growth), a scientific method for evaluating green growth must be devised [13]. Recognizing the manufacturing sector's development stage and determining whether it is experiencing gray or green growth is crucial for China's sustainable development.

Therefore, this paper attempts to answer the following questions. What is the current state of green growth in China's manufacturing industry: gray growth or green growth? Are there industry heterogeneity issues? What are the main reasons for the difference in efficiency? Based on the above issues and the existing research, this paper conducts research from the following aspects. Firstly, a super-efficiency slacks-based measure model is proposed to evaluate green growth efficiency of 27 manufacturing industries in China. Secondly, the Luenberger index is used to decompose the drivers of green growth. Finally, we analyze the results and industry heterogeneity and propose recommendations and suggestions for the future development of the manufacturing industry from the perspective of the government and enterprises.

2. Literature Review

2.1. Green Growth Theory

At the 2005 United Nations Economic and Social Conference for Asia and the Pacific, the idea of "green growth" was first put forth. Since then, numerous well known international organizations (Organization for Economic Co-operation and Development (OECD), United Nations Environment Programme (UNEP), Global Green Growth Institute (GGGI), etc.) have been investigating green growth in various ways. They emphasize the promotion of a strategy for green growth and the execution of pertinent strategies, while academics focus more on the trajectory of growth and state assessment.

The theory of green growth's first contribution is to encourage economic expansion. After the 2008 financial crisis, the green growth theory was first primarily used to encourage short-term economic recovery [14,15]. Some of the economies that had undergone recessionary shocks promoted a return to growth through a number of environmental improvement initiatives. The study also discovered that green growth was successful in boosting economic production and employment growth, which led researchers to conclude that green growth could help accelerate economic growth in the medium to long term. The second contribution is the expansion of growth's causes and mechanisms. The main contributions of technical innovation, green finance, and other factors to green growth have been highlighted through research. Bradley Loewen explored three European Union policy responses to regional energy transitions through coal, green growth, and crises [16]. Isaac K developed a framework of green growth and links sustainable development to environmental sustainability and socioeconomic sustainability [17]. Xu explored the relationship between the environmental technologies and green growth in BRICS economies [18]. Jouvet P believed that the resource efficiency, utilization of renewable energy, and resource cost are important changes from theory to practice of green growth [19]. Satbyul Estella Kim chose indicators, such as the proportion of greenhouse gas emissions in GDP, the proportion of the tertiary industry in GDP, energy consumption per unit GDP, and the proportion of renewable energy, to measure green growth [20]. Although experts and scholars have different research priorities, they have a consensus on green growth: it is a restrained and inclusive economic growth, emphasizing the maximum use of resources and the minimum cost of the environment [21].

2.2. Scale Effect and Technological Effect in EKC

Green growth theory places an emphasis on sustainable economic growth with a decoupling from resources and the environment. While EKC theorizes the connection between economic growth and green growth, it actually illuminates the circumstances under which economic growth can attain green growth [22,23]. In fact, technical progress, as a major force behind economic growth, has a significant impact on changing the pace of economic growth and fostering industrial change. According to EKC, the scale, technology, and structural effects of economic expansion have an impact on environmental quality, and the role that technological progress plays in fostering this impact is a growing source of concern. The question of whether technical progress has considerably increased green growth is at the center of the present discussion, and there are three basic viewpoints. (1) Technological progress is the core driver of green growth. When explaining the mechanism of EKC formation, Grossman and Krueger first proposed the "technology effect", contending that as a nation's economy grows, technological advancement will increase productivity and resource efficiency, decrease factor inputs in the production process, and weaken the impact of production on the environment. They also claimed that the creation, use, upgrading, and replacement of dirty technologies will also effectively reduce pollution. Then, a large portion of the literature supported the use of technological innovation based on the EKC curve, claiming that it is a required condition for the EKC curve's inflection point and an unavoidable means of resolving environmental issues. (2) Technological progress is not a core driver of green growth. It is believed that the pursuit of production efficiency rather than environmental pollution drives technological advancement, that the scale of economic development will consume a lot of scarce non-renewable resources, and that technological advancement, while it may increase productivity, may also create new sources of pollution, limiting the impact of technology on EKC. Even if the environment may have improved in this instance, this is only a transient occurrence brought on by technical constraints. (3) The contribution of technology progress to promoting green growth is unclear. With non-linear relationships, such as N-shaped and inverted U-shaped, and their effects possibly being related to other factors, such as economic development stage, finance, and scale, researchers believe that there is no effect, positive and negative effects co-existing, between technological innovation and environmental pollution.

2.3. Green Growth in Manufacturing Industry

The majority of China's manufacturing industry is currently in the extensive stage, with enormous emissions of environmental pollution and a poor rate of complete resource use. This type of progress cannot continue [24]. For the long-term development of the manufacturing industry, the concept of green growth is more appropriate [25]. From the reality of the development of manufacturing industry, the power source of green growth of manufacturing industry mainly comes from three aspects [26–28]. The first is the demand for energy conservation and emission reduction. To prevent the expansion of industries that produce a lot of pollution and use a lot of energy, the state has implemented a variety of environmental regulations. The second is to realize the green transformation of the industry. The market position of new industries in conventional polluting industries is being improved, which is encouraging the environmental protection industries, high-tech industries, new generation information technology, high-end equipment, and other industries to boost their economic contributions. The third is traditional industries' green output, which is propelled by innovation. The traditional manufacturing industry has engaged in several technological innovation initiatives to transform in order to achieve green growth. The whole life cycle of the manufacturing industry has been impacted by several green initiatives, including green manufacturing, green logistics, green design, green operation, and green supply chain.

Efficiency analysis can be divided into static efficiency and dynamic efficiency. While dynamic efficiency concentrates on the direction and long-term development potential of efficiency changes, static efficiency concentrates on the effectiveness of resource allocation of decision-making units in the near term. "Green growth efficiency in manufacturing industry" emphasizes that the economic benefit of output is the largest and the cost of resources and environment is the smallest when production elements, such as labor, capital, and energy production, are invested, according to the concept and connotation of green growth in the manufacturing industry and the characteristics of efficiency theory. Yeh Jiahuey examined total-factor green growth performance, including the energy efficiency and carbon shadow price of China's chemical sector [5]. Due to the improvement of DEA methods, Chen investigated the direct effect and spillover effect between green efficiency and Co_2 emission abatement policy [28]. Song developed a directional distance function model to explore the regional evaluation of green output in China [29]. With the aid of the DEA and Malmquist index, Sueyoshi examined the effectiveness of green growth and concluded that economic activity not only produced desired outputs, such as electricity, but also undesired outputs such as carbon dioxide emissions [30].

Overall, most of the research on green growth in the manufacturing industry has focused on efficiency, which is used to identify the growth state [31]. In terms of efficiency measurement, DEA was used to quantify the efficiency of green growth. However, there may be issues with overestimation of efficiency and the inability to alter input-output efficiency nonproportionally. In terms of the research content, the examination of the effectiveness of green growth concentrates on the examination of the state, but the exploration of the underlying power is rather minor.

Efficiency theory, which first placed an emphasis on labor productivity and capital productivity in the production process, is widely employed in social and economic life. Efficiency in green growth emphasizes both the best use of available resources and the efficiency of labor and capital [32,33]. The "input–output" analytical framework, which often bases models on production or cost functions, is the prevalent paradigm for measuring efficiency. Based on the research of Cole et al., the "supply–demand" equilibrium model of manufacturing pollution emissions is built in this work. In order to meet the demand for resources from production activities, the energy input is integrated into the production function, and the environmental pollution is recorded as an output, which is regarded as the social and ecological cost. Therefore, based on the production function, this study builds an input–output system to assess the manufacturing industry's green growth efficiency by using labor, capital, and energy as input variables and economic target and environmental pollution as output variables. Due to the industry specificity of the manufacturing industry, the dominant factors of various industries differ from one another. Consequently, industry heterogeneity analysis is conducted in accordance with the characteristics of factors to identify the major drivers of labor, capital, and technology factor-led manufacturing enterprises to achieve green growth.

3. Methodology

3.1. Production Possibility Set

The production frontier represents the boundary formed by the set of maximum output under the condition of fixed input or the set of minimum input under the condition of fixed output [34]. The frontier production function represents the relationship between the maximum output and a given input, and the average production function is the relationship between the current input and output. The frontier production function is the optimal state. The average production function, which is below the frontier production function, assesses the input–output situation at hand. All of the sample sites are below the frontier production function (Figure 1).

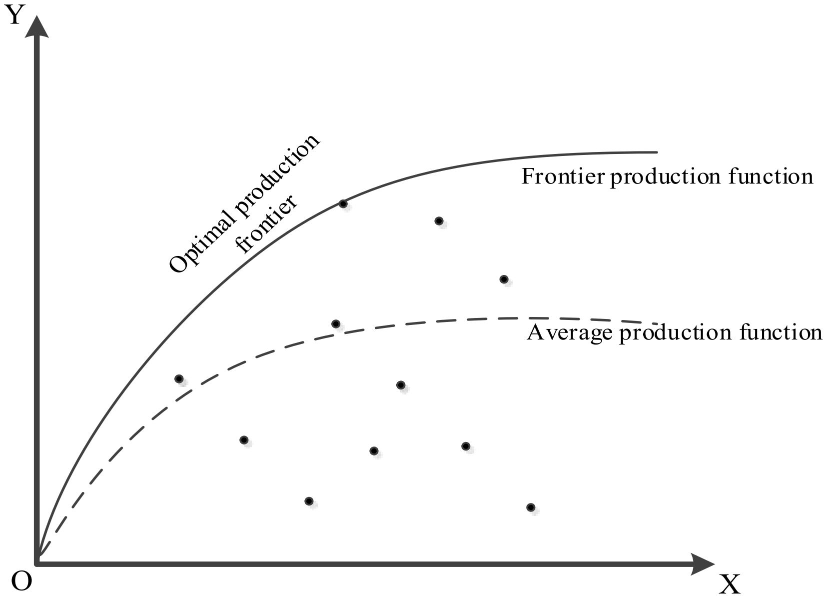


Figure 1. Frontier production function principle.

A production possibility frontier taking into account capital, energy, other inputs, projected output, and undesirable outputs, is known as the production frontier of manufacturing green growth efficiency. Each manufacturing industry is viewed as a decision-making unit. This study develops a production possibility set that encompasses both the desirable (good output) and undesirable (poor output) outcomes of resource consumption and pollution emissions. It also combines resource and environmental restrictions into the framework of green development efficiency.

It is assumed that there are k manufacturing industries, each industry has n inputs and m outputs, denoted by $x = (x_1, \ldots, x_n) \in R_N^+$ and $y = (y_1, \ldots, y_m) \in R_M^+$, accompanied by i undesirable outputs $b = (b_1, \ldots, b_i) \in R_I^+$. In each period, the set of production possibilities $k\, k = 1, \ldots, K$ for the primary industry can be expressed as $P(x) = (x^{k,t}, y^{k,t}, b^{k,t})$:

$$P(x) = \{(y, -b) : x\, canproduce(y, -b)\}, x \in R_N^+ \tag{1}$$

According to Fare and Wang [35], we assume that the production possibility set is a closed set bounded set, and the desirable output and undesirable output are freely disposable. Now, then we propose two environmental axioms:

1. “Zero Combination” Axiom. If $(y, b) \in P(x)$ and $b = 0, y = 0$. It means that if there is an industry without undesirable output, there is undesirable output. Or it can be understood that when there is a desirable output, there must be undesirable outputs,

such as resource consumption and pollution emissions. So, we can put the element of resources and environment into the analytical framework.

2. Weakly Disposable Axiom. If $(y, b) \in P(x)$ and $0 \leq \theta \leq 1$, $(\theta y, \theta b) \in P(x)$ It shows that the balance between desired and undesirable production changes, which suggests that, in the industrial sector, if we want to lessen environmental pollution or eliminate undesirable output, we must invest a certain amount of money and resources.

Therefore, assuming that in each period $t = 1, \ldots, T$, the input and output value of the $k = 1, \ldots, K$ industry is $(x^{k,t}, y^{k,t}, b^{k,t})$, the production possibility set model that satisfies the above axioms and is constrained by the resource environment can be expressed as follows.

$$P^t(x^t) = \left\{ \begin{array}{l} (y^t, b^t) : \\ \sum\limits_{k=1}^{K} z_k^t b_{ki}^t \geq b_{ki}^t, i = 1, \ldots, M; \\ \sum\limits_{k=1}^{K} z_k^t y_{km}^t \geq y_{km}^t, m = 1, \ldots, M; \\ \sum\limits_{k=1}^{K} z_k^t x_{kn}^t \geq x_{kn}^t, n = 1, \ldots, N; \\ z_k^t \geq 0, k = 1, \ldots, K \end{array} \right\} \tag{2}$$

z_k^t is the weight of each cross-sectional observation. Non-negative weight variable indicates constant return to scale of production technology. The two conditions are:

- $\sum\limits_{k=1}^{K} b_{ki}^t > 0, i = 1, \ldots, I$, at least one industry produces each undesirable output.
- $\sum\limits_{i=1}^{I} b_{ki}^t > 0, k = 1, \ldots, K$, each industry produces at least one undesirable output.

3.2. Super-Efficient SBM Model

The super-efficient SBM model expands on conventional SBM calculations in order to conduct comparisons in effective decision-making units and to account for undesirable outputs. As a result, in the green manufacturing industry development process, the super-efficient SBM model is utilized to deal with undesirable outputs, such as wastewater and waste gas, while ranking the efficient decision units according to the efficiency value, breaking the restriction of efficiency value of 1 [36].

$$\begin{array}{l} \min \rho = \dfrac{1+\frac{1}{m}\sum_{t=1}^{m} \frac{s_i^-}{x_{ik}}}{1-\frac{1}{q_1+q_2}\left(\sum_{s=1}^{q_1} \frac{s_r^+}{y_{rk}}+\sum_{t=1}^{q_2} \frac{s_t^{z-}}{z_{tk}}\right)} \\ s.t. \\ \sum\limits_{j=1,\neq k}^{n} x_{ij}\lambda_j - s_i^- \leq x_{ik}, \\ \sum\limits_{j=1,\neq k}^{n} y_{rj}^d\lambda_j + s_r^+ \geq y_{rk}^d, \\ \sum\limits_{j=1,\neq k}^{n} z_{tj}^u\lambda_j - s_t^{z-} \leq z_{tk}, \\ \frac{1}{q_1+q_2}\left(\sum_{s=1}^{q_1} \frac{s_r^+}{y_{rk}} + \sum_{t=1}^{q_2} \frac{s_t^{z-}}{z_{tk}}\right) > 0; \\ s^-, s^+, \lambda > 0 \\ i = 1, 2, \cdots, m; s = 1, 2, \cdots, q_1; \\ t = 1, 2, \cdots, q_2; j = 1, 2, \cdots, n, (j \neq k) \end{array} \tag{3}$$

(x, y, z) is the input, desirable output, and undesirable output. (s_i^-, s_r^+, s_t^{z-}) represents the slack variables of input, desirable output, and undesirable output. ρ is the green growth efficiency of the evaluation unit.

3.3. Luenberger Productivity Index

In line with the Luenberger productivity index approach in Chamber, the green growth Luenberger productivity index (GGL), proposed in this paper, was constructed as follows [37]:

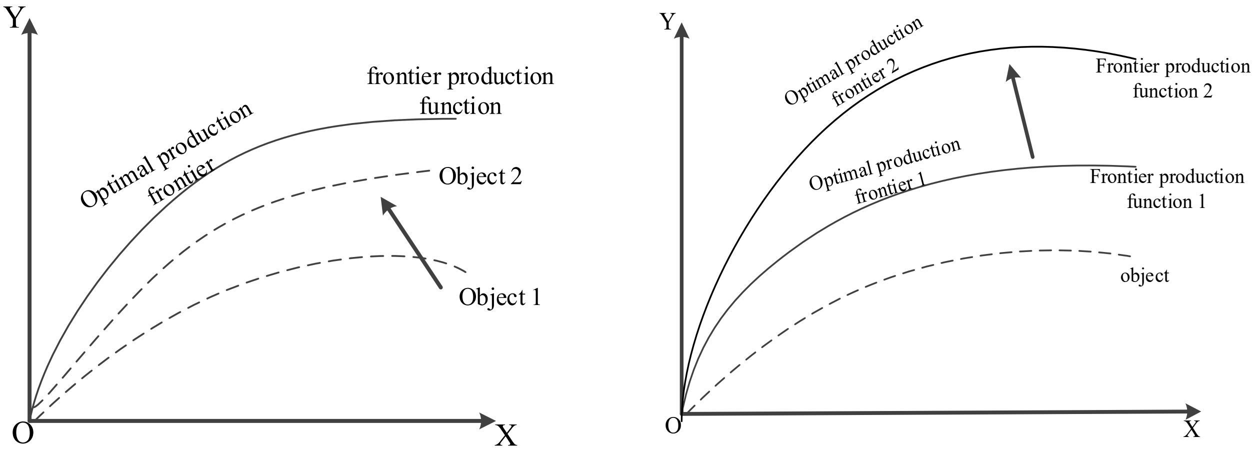
$$GGL_t^{t+1} = \frac{1}{2}\left\{\left[S_c^t(x^t, y^t, b^t; g) - S_c^t(x^{t+1}, y^{t+1}, b^{t+1}; g)\right] + \left[S_c^{t+1}(x^t, y^t, b^t; g) - S_c^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; g)\right]\right\} \tag{4}$$

$$GGL_t^{t+1} = TE_{\mathrm{t}}^{t+1} + TP_t^{t+1} \tag{5}$$

$$TE_t^{t+1} = S_c^t(x^t, y^t, b^t; g) - S_c^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; g) \tag{6}$$

$$TP_t^{t+1} = \frac{1}{2}\left\{\left[S_c^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; g) - S_c^t(x^{t+1}, y^{t+1}, b^{t+1}; g)\right] + \left[S_c^{t+1}(x^t, y^t, b^t; g) - S_c^t(x^t, y^t, b^t; g)\right]\right\} \tag{7}$$

GGL can be decomposed into the technology efficiency (TE) and the technology progress (TP). TE is the maximum possible distance between the decision-making unit and the production frontier, from t to t + 1, representing the change in the relative efficiency of the producer (Figure 2a). TP is the movement of the production frontier from t to t + 1, indicating the movement of the production technology frontier level (Figure 2b). If GGL >(<) 0, this indicates gain (loss) in green growth efficiency. If TE >(<) 0, it means efficiency has been improved (deteriorated). If TP >(<) 0, it indicates technological progress (technological regression).



(**a**) (**b**)

Figure 2. This is the change principle of TE and TP: (**a**) the change in TE; (**b**) the change in TP.

3.4. Research Object and Index Selection

3.4.1. Research Context: Green Growth in the Manufacturing Industry

It is critical to alter China's economic development model as the conflict between economic expansion, resource depletion, and environmental pollution worsens. The manufacturing industry has been integrally involved in all facets of the changes in social and economic life since the first industrial revolution in the 18th century and is a crucial and essential component of people's productive lives. The presence of a highly developed manufacturing industry is one of the key indicators of a nation's overall strength; manufacturing status is crucial [38,39]. The expansion of the manufacturing industry has made significant advancements since the reform and opening up of China's economy into a high-speed growth mode, and China has established itself as a "global manufacturing power". However, while the manufacturing industry has made remarkable achievements, there are also problems, such as weak international competitiveness and low added value of related products. It continues to struggle with overcoming the broad development model that is characterized by energy consumption, emissions, challenging circulation, and low efficiency. It is critical to determine the manufacturing industry's current green growth status, identify its drivers influencing the growth, and assist it in changing its development model. An effective way to assess the manufacturing industry's current green growth level is to look at green growth efficiency. Based on a review of the literature and the relevant theoretical research, it was discovered that, in addition to increasing production value, reducing resource consumption and environmental pollution is also essential for attaining green growth in the manufacturing industry. The green growth effectiveness of the manufacturing industry is measured from the standpoint of taking into account "green" and "growth", which form the study concepts of this article.

3.4.2. Research Object

Due to changes in the classification and statistical standards of the data statistics industry in 2012, the similar industries are merged, and missing data industries are removed. This paper identifies 27 manufacturing industry objects (2005–2017) in total. The data come from China Industrial Economic Statistics Yearbook, China Energy Statistics Yearbook, and the Environmental Statistics Yearbook.

3.4.3. Industry Classification

According to the classification of resource intensity and the United Nations Standard International Trade Classification: SITC, this paper divides 27 manufacturing industries into three types: labor-intensive, capital-intensive, and technology-intensive. The specific classification is as follows (Table 1).

Table 1. Classification of manufacturing industry.

Labor-Intensive	Capital-Intensive	Technology-Intensive
Agricultural and sideline food processing (AS)	Furniture (FM)	Chemical raw materials and chemical products (CC)
Food	Paper making and paper products (PP)	Pharmaceutical
Wine, beverage, and refined tea (WBR)	Printing and recording media reproduction (PR)	Chemical fiber (CF)
Tobacco products (TP)	Culture and education, arts and crafts, sports, and entertainment products (CACSE)	General equipment (GE)
Textile	Petroleum processing, smelting, and nuclear fuel processing (PSN)	Special equipment (SE)
Textile and clothing (TC)	Rubber and plastic products (RP)	Railway, ship, aerospace, and other transportation (RSAT)
Leather, fur, feathers, and their products and footwear (LFFF)	Non-Metallic mineral products (NMM)	Electrical machinery and equipment (EME)
Wood processing and wood, bamboo, rattan, palm, and grass products (WWBRPG)	Ferrous metal smelting and rolling processing (FMSR)	Computer, communication, and other electronic equipment (CCE)
	Non-Ferrous metal smelting and rolling processing (NFMSR)	Instrument
	Metal products (MP)	

3.4.4. Index Selection

1. Input index
    - Labor input: when measuring labor input, it is necessary to obtain the labor input of various industries. Since it is impossible to obtain statistical indexes including labor time and labor efficiency, the average number of employees in the manufacturing industry is selected as the index of labor input in this paper.
    - Capital input: the estimation of capital stock is calculated by the value of fixed assets in the perpetual inventory method. In this paper, the annual average balance of net fixed assets of industrial enterprises above designated size is

selected to approximately replace the investment in fixed assets, and the missing data of net fixed assets are approximately estimated by the average value.

- Energy input: energy element represents the degree of resource consumption in the development of manufacturing industry. In this paper, the total energy consumption of the manufacturing industry is selected as the index of energy input.

2. Output index
    - Desirable output: since resource consumption and environmental pollution exists in all aspects of the production process, the total output value of the industry contains the energy factor of the nature of intermediate inputs, including both the production part of added value and the intermediate input part. Therefore, the total industrial output value is selected as the index of desirable output in this paper.
    - Undesirable output: the entropy method is used to synthesize the environmental pollution index to calculate the undesirable output. The environmental pollution index is composed of three indicators: wastewater discharge, exhaust gas discharge, and solid waste discharge. It is used to quantify the harm that pollutants released during manufacturing activities have on the environment.

The descriptive statistical characteristics of input-output indexes are as Table 2.

Table 2. Descriptive statistical characteristics of input-output indexes.

Index		Avg.	S.D.	Min.	Max.
Input index	Capital Stock	3974.271	4287.587	59.0448	24,825.4
	Average number of employees	253.8858	184.1726	15	909.26
	Total energy consumption	4737.796	10,422.49	65.8392	67,051.67
Desirable output	Total industrial output value	4204.416	5703.454	117.354	44,897.7
Undesirable output:	Wastewater discharge	60,008.19	89,417.85	298	424,597
	Exhaust emissions	10,390.23	27,486.46	20.64	185,327.9
	Solid waste emissions	2568.632	7016.641	2	44076
	environmental pollution index	0.111962	0.19453	1.28×10^{-5}	0.896436

4. Results and Discussion

4.1. Efficiency Analysis

The green growth efficiency values of 27 manufacturing industries are shown in Table 3. The research finds that there are significant differences in the green growth efficiency of each manufacturing industry. The specific analysis is as follows.

Table 3. Green growth efficiency of China's manufacturing industry in 2005–2017.

Industry	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Average	Growth State
TP	2.035	2.244	2.637	2.843	3.073	3.302	3.315	3.338	2.834	3.135	2.897	2.764	2.780	2.861	Dark Green Growth
FM	1.359	1.457	1.279	1.116	1.050	1.011	1.036	0.627	1.778	6.012	1.046	1.616	1.293	1.591	
CCE	1.438	1.489	1.498	1.506	1.459	1.459	1.427	1.439	1.475	1.492	1.494	1.480	1.491	1.473	
Instrument	1.511	1.351	1.243	1.178	1.103	1.018	1.012	0.529	1.182	1.109	1.762	1.339	1.422	1.212	
CACSE	1.000	3.105	1.000	1.000	1.000	1.000	3.000	1.000	1.203	0.512	0.362	0.487	0.340	1.155	
PR	1.008	1.186	1.145	1.243	1.121	1.139	1.145	1.098	1.088	1.050	1.036	1.055	0.544	1.066	
EME	0.421	0.409	0.462	1.030	1.078	1.073	1.135	1.148	1.041	1.008	0.698	0.733	0.748	0.845	Light Green Growth
Textile	0.272	0.284	0.304	0.288	1.032	1.037	1.042	1.040	0.271	1.019	1.014	1.005	1.007	0.740	
NFSR	0.161	0.174	0.195	0.206	0.231	0.185	1.192	1.162	1.108	1.130	1.118	1.145	1.258	0.713	
RSAT	0.289	0.267	0.273	0.287	0.379	0.362	0.389	0.438	1.056	1.107	1.149	1.169	1.154	0.640	

Table 3. *Cont.*

Industry	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**Average**	**Growth State**
CF	0.317	0.276	0.245	0.241	0.241	0.261	0.351	1.002	0.272	0.284	0.255	0.302	0.295	0.334	Gray Growth
LFFF	0.473	0.384	0.394	0.369	0.354	0.325	0.332	0.321	0.333	0.257	0.242	0.239	0.236	0.328	
WWBRPG	0.366	0.335	0.359	0.359	0.314	0.242	0.245	0.232	0.237	0.239	0.225	0.216	0.215	0.276	
GE	0.182	0.175	0.185	0.202	0.236	0.199	0.206	0.226	0.255	0.437	0.488	0.381	0.350	0.271	
SE	0.244	0.225	0.237	0.250	0.280	0.239	0.225	0.257	0.272	0.307	0.292	0.284	0.270	0.260	
Pharmaccutical	0.261	0.248	0.247	0.241	0.252	0.243	0.258	0.259	0.254	0.277	0.268	0.260	0.250	0.255	
TC	0.391	0.304	0.316	0.275	0.253	0.217	0.226	0.224	0.232	0.199	0.189	0.186	0.179	0.245	
MP	0.234	0.201	0.200	0.196	0.201	0.166	0.172	0.180	0.178	0.167	0.164	0.160	0.173	0.184	
NFMSR	0.184	0.167	0.165	0.184	0.175	0.154	0.234	0.179	0.144	0.169	0.189	0.204	0.240	0.184	
CC	0.166	0.178	0.178	0.173	0.211	0.179	0.205	0.197	0.175	0.179	0.179	0.179	0.190	0.184	
AS	0.238	0.218	0.229	0.230	0.213	0.158	0.167	0.159	0.133	0.134	0.120	0.115	0.116	0.172	
Food	0.236	0.204	0.198	0.182	0.169	0.148	0.144	0.140	0.140	0.137	0.125	0.125	0.119	0.159	
WBR	0.215	0.184	0.182	0.172	0.161	0.148	0.147	0.150	0.151	0.145	0.131	0.134	0.132	0.158	
NMM	0.093	0.095	0.104	0.114	0.136	0.126	0.128	0.139	0.130	0.132	0.130	0.125	0.126	0.121	
PP	0.158	0.139	0.127	0.119	0.113	0.102	0.106	0.104	0.104	0.107	0.105	0.114	0.116	0.117	
PSN	0.145	0.127	0.106	0.089	0.085	0.072	0.070	0.060	0.051	0.051	0.051	0.054	0.063	0.079	
RP	0.128	0.105	0.095	0.083	0.077	0.064	0.068	0.064	0.063	0.063	0.059	0.060	0.061	0.076	
Average	0.501	0.575	0.504	0.525	0.555	0.542	0.666	0.582	0.598	0.773	0.585	0.590	0.562	0.581	

4.1.1. Fluctuation State and Unstable Upward Trend

The findings (Table 3) show that, from 2005 to 2017, the average green growth efficiency across 27 manufacturing industries varied from 0.501 to 0.773, with an average of 0.581. Efficiencies are generally poor. From the average change (Figure 3), there is a fluctuation state and unstable upward trend. The first stage range from 2005 (0.501) to 2014 (0.773) was represented by a 6% growth rate. China started to enter a phase of macroeconomic policy adjustment in 2005, putting a strong emphasis on resource efficiency, rapidly expanding the equipment manufacturing sector, and enhancing the effectiveness of green growth. From 2014 to 2017, the second stage saw a reduction in efficiency. The Chinese Environmental Protection Law, which was enacted in 2014 and is the strictest environmental protection law ever adopted, severely restricted resource use and pollutant emission issues in manufacturing, which caused green growth efficiency to rapidly fall after that year.

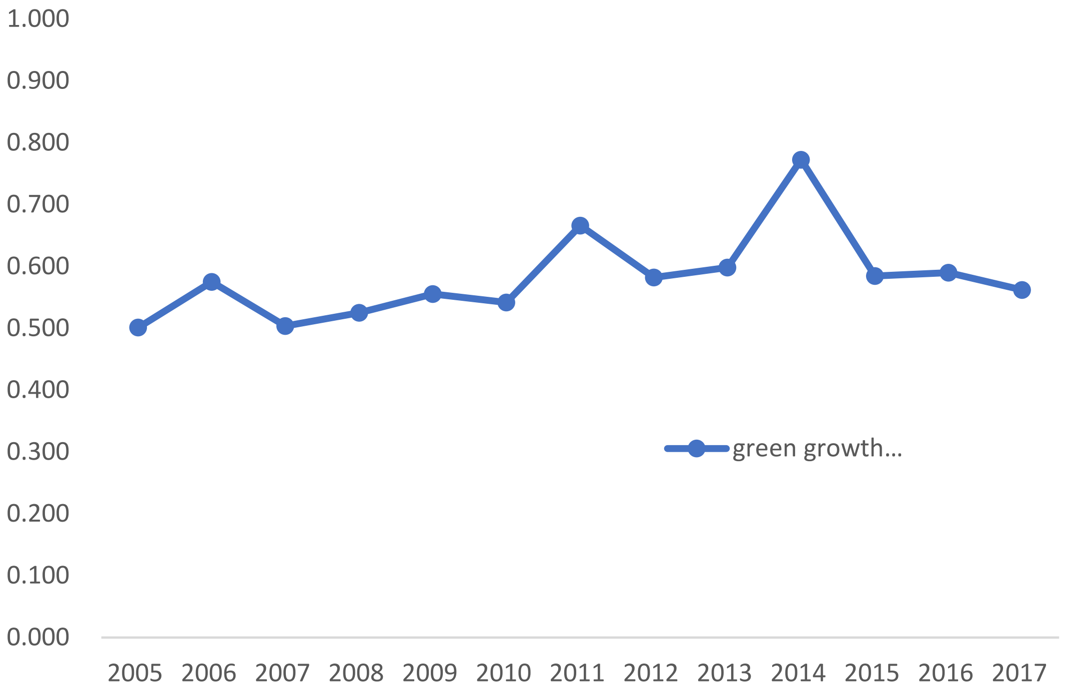


Figure 3. Average change in green growth efficiency on manufacturing industry in 2005–2017.

4.1.2. Growth State

Classifying the industries in accordance with the outcomes of the super-efficiency is important in order to effectively highlight the similarities and differences between industries. The Fifth Plenary Session of the 18th Central Committee of the People's Republic of China proposed to adhere to the concept of "dark green" and "light green" development, with "dark green" emphasizing the harmony of economy, society, and nature, which is the optimal state of green development, and "light green" emphasizing localization, which is the excessive stage of development to dark green [40]. We can determine, from Figure 1, that an efficiency value of 1 is necessary to reach the production frontier, which is the optimal state. As a result, we use 1 as the standard to determine if an industry has achieved green growth; any value above 1 is referred to as dark green growth. With a mean value of 0.581, the overall green growth state is believed to be generally steady. As a result, we consider states above the mean value that are near the optimal production frontier to have strong potential for green growth and are referred to as light green states, while states below the mean value are seen as having a poor development state and are classified as gray growth (Table 4).

Table 4. Classification for growth state.

Green Growth Efficiency	Growth State
≥ 1	Dark green growth
0.581~1	Light green growth
<0.581	Gray growth

- Deep green growth: these six industries are clustered as deep green growth, and all of their efficiencies are above 1. They are TP (2.861), FM (1.591), CCE (1.473), Instrument (1.212), CACSE (1.155), and PR (1.066). These industries consume few resources and generate relatively less pollution, according to the previous statistics.
- Light green growth: these four businesses are categorized as being in a light green growth state, since their green growth efficiency values range from 0.581 to 1. What these industries have in common is the high level of technology required, but, at the same time, the industry's resource and energy consumption is also relatively high.
- Gray growth: this contains 17 industries that we classify as being in a gray growth condition because their mean green growth efficiency values are significantly below the industry average, ranging from 0.076 to 0.334. The number of industries in gray growth accounted for more than 60%. This indicates that most of the manufacturing industries have not achieved green growth and are still in a state of gray growth. There is still much room for improvement in the green road of China's manufacturing industry, and most industries still have not eliminated the production dilemma of high emissions.

4.1.3. Industry Heterogeneity

Figure 4 shows the average change in three types of manufacturing industries. According to the broken line change, the green growth efficiency of technology-intensive industries shows an upward trend. Capital-intensive and labor-intensive industries exhibit significant fluctuations. This indicates that the industry development model driven by labor and capital cannot meet the current demand for green growth in the manufacturing industry. Technological innovation is the key driving force affecting the realization of green growth in the manufacturing industry.

- Labor-intensive industry: this includes eight industries, including AS, WBR, TP, Textile, and some others. From 2005 to 2012, it showed a rather steady increasing trend; starting in 2012, the trend began to turn downward. The labor-intensive industry has a lower level of technical innovation and is highly reliant on the need for labor resources. For the implementation of green growth in labor-intensive industries, the development model of population dividends as a source of competitive advantage is no longer appropriate.

- Capital-intensive industry: this include 10 industries, such as FM, PP, PR, metal, transportation, iron, steel, and other basic industries. A typical industry is the heavy chemical industry. Capital-intensive industry has a lower rate of green growth than labor-intensive industries. With the exception of 2006, 2011, and 2014, most of them are in a condition of gray growth, with an average green growth efficiency of less than 0.5. Producing requires a substantial investment of capital. Capital-intensive sectors exhibit glaring green development disadvantages since they rely on investment-driven industry growth models, such as capital advantages and processing trade.
- Technology-intensive industry: this includes nine industries, such as CC, CF, GE, an SE, which belong to high-tech industrial sectors. Its technical knowledge accounts for a large proportion, and scientific research funds, labor education, and product added value are all significant contributors. Technology-intensive industries have shown a clear increase trend in green growth efficiency from 2005 to 2017. Among the three different types of industries, this is the only one to generate green growth. This further illustrates the significance of technological innovation in the green growth of the manufacturing industry. Technology dominance is the most efficient approach to increase the value of businesses, and it is also the primary driving force to increase the efficiency of green growth.

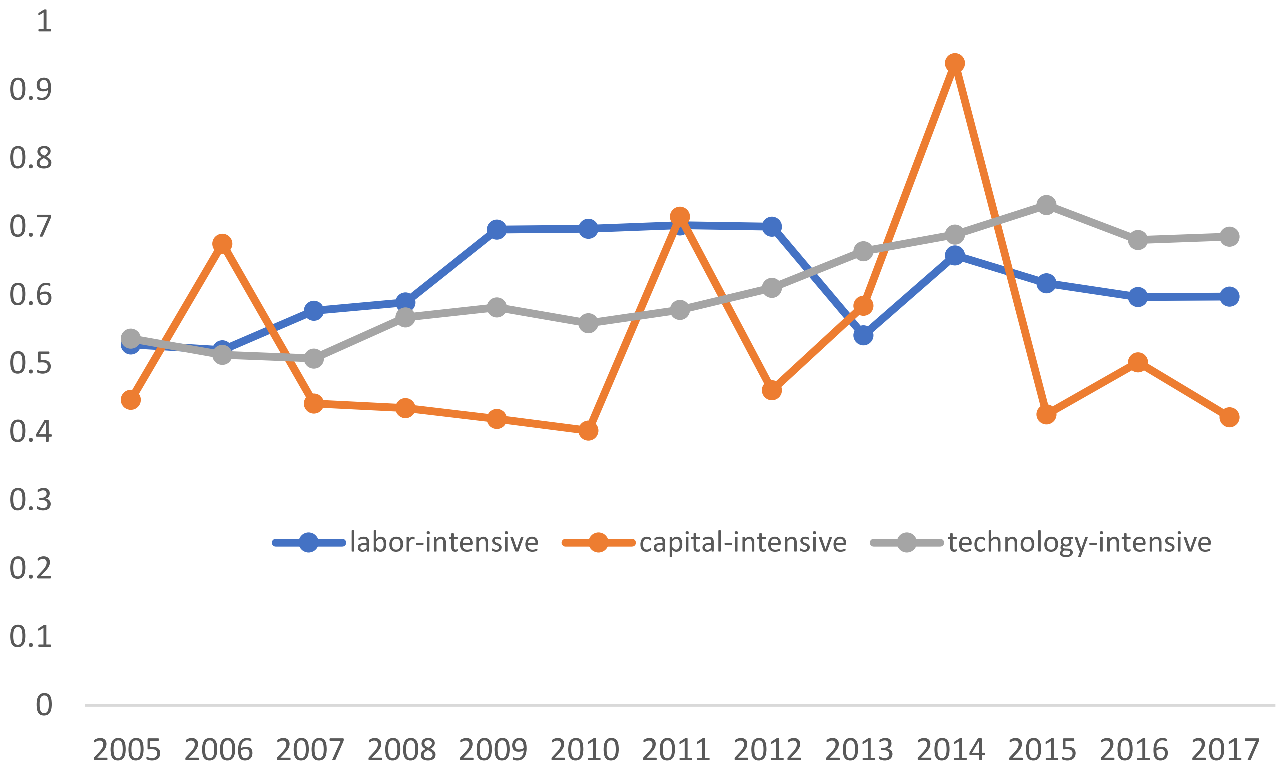


Figure 4. Industry heterogeneity results of green growth efficiency.

4.2. The Discussion of Driving Force

As indicated in Table 5, the TE and TP are generated by breaking down the growth rate of green growth efficiency (as determined by the Luenberger index) of manufacturing subsectors.

The TE and TP are obtained by decomposing the growth rate of green growth efficiency (calculated by Luenberger index) of manufacturing sub sectors, as shown in Table 5. The change in TE is manifested in the allocation of industrial resources, structural adjustment, management efficiency improvement, institutional reform, etc. (the relative position change in each industry and the production frontier boundary: Figure 2a). The change in TP mainly refers to the introduction of new technologies or R&D generated by relying on technology introduction or independent innovation, imitation innovation, etc., which is manifested in improving productivity to obtain first-mover advantage (the movement of the production frontier boundary: Figure 2b).

Table 5. The results of GGE, TE, and TP.

Number	Manufacturing Industry	GGE	TE	TP
1	AS	0.0045	−0.0119	0.0164
2	FOOD	0.0182	−0.0048	0.0230
3	WBR	0.0226	−0.0028	0.0254
4	TP	0.0176	0.0104	0.0072
5	Textile	0.0786	0.0049	0.0737
6	TC	0.0266	−0.0075	0.0341
7	LFFF	0.0142	−0.0086	0.0228
8	WWBRPG	0.0711	0.0020	0.0691
9	FM	0.1054	0.0087	0.0966
10	PP	0.0154	−0.0003	0.0157
11	PR	0.1055	0.0051	0.1004
12	CACSE	−0.0289	−0.1156	0.0867
13	PSN	0.0002	−0.0060	0.0062
14	CC	0.0114	−0.0028	0.0142
15	Pharmaceutical	0.0410	−0.0060	0.0470
16	CF	0.0729	0.0038	0.0691
17	RP	0.0052	−0.0024	0.0076
18	NMM	0.0101	−0.0003	0.0105
19	FMSR	0.0896	0.0087	0.0809
20	NFMSR	0.0199	−0.0018	0.0217
21	MP	0.0247	−0.0064	0.0311
22	GE	0.1044	0.0031	0.1013
23	SE	0.0983	0.0000	0.0984
24	RSAT	0.1091	0.0166	0.0925
25	EME	0.0935	−0.0010	0.0945
26	CCE	0.0117	−0.0258	0.0375
27	Instrument	0.0371	0.0063	0.0307
	Average	0.04369	−0.0049	0.0486

4.2.1. The Discussion of Growth Rate

According to the growth rate, during the sample period from 2005 to 2017, the average growth rates of GGE, TE, and TP were 4.369%, −0.490%, and 4.86% (Table 5). There has been a negative growth in TE and positive growth in TP. It can be seen that the growth of green growth efficiency is mainly driven by technological progress, rather than the improvement of technical efficiency. The production possibility set (Figure 1) constrained by resource and environment shows that technological progress is related to the optimal production boundary, and technological progress can promote the expansion of the production frontier in a better direction. According to the static analysis of green growth efficiency (Table 3), it was found that the green growth efficiency of China's current manufacturing industry exhibits significant fluctuation in terms of green growth efficiency. The split results (Table 5) of the green growth efficiency growth rate of manufacturing industries in 2005–2017 further prove the importance of technological progress. On the one hand, it shows that the technological progress caused by technological innovation has an important impact on the development of green growth in the manufacturing industry. Under the constraints of decreasing resources and increasing environmental pressure, China 's manufacturing industries have paid more in technological innovation in order to reduce resource consumption and achieve effective economic growth. On the other hand, it also shows that there is a huge space for improvement in the technical efficiency of China's manufacturing industry.

4.2.2. The Discussion of TE and TP

The growth rate of TP in all manufacturing industries is greater than 0, resulting in different degrees of technological progress (Table 5). An amount of 16 of the 27 sub-sectors of the TE are negative, accounting for about 60% of manufacturing industry, indicating that more than half of the manufacturing industry produced a deterioration in technical efficiency. In terms of the change in TE and TP, the technological progress of heavy industry represented by ferrous metal smelting and the calendering industry and high-tech industry, which themselves are represented by electrical machinery and equipment manufacturing, general equipment manufacturing, computer, communication, and other electronic equipment manufacturing, increased significantly. According to the characteristics of the industry, it can be found that heavy industry improves the efficiency of green growth by improving production efficiency, while high-tech industry improves the efficiency of green growth by introducing new technologies through research and development. The TP index drives the industry to achieve green growth by continuously creating new frontier production surfaces. As far as the change in technical efficiency is concerned, the light industry mainly invested in labor and capital has deteriorated its technical efficiency. The side effect of technological progress on industrial upgrading is the improvement of production efficiency and the continuous improvement of the system.

4.2.3. The Discussion of Industry Heterogeneity

There are obvious differences in the changes of green growth efficiency of the three types of manufacturing industries (Figure 5).

(1) The green growth efficiency of the three types of manufacturing has achieved positive growth, and the technology-intensive component still dominates in the process of the manufacturing industry.
The growth rates of the three types of industries are higher than zero when viewed in terms of the total manufacturing green growth efficiency growth rate. The manufacturing industry is growing consistently. Technology-intensive industries have the fastest growth rate (6.535%), followed by capital-intensive industries (3.382%), and labor-intensive industries (3.169%) have the slowest growth rate. Table 3 demonstrates that industries that rely heavily on technology have the highest rates of green growth efficiency. All of this suggests that technologically advanced industries hold a significant place in China's manufacturing industry.

(2) The TE in labor-intensive and capital-intensive industries is deteriorating, but it is improving in the technology-intensive industries.
Labor-intensive industries (−0.228%) and capital-intensive industries (−1.159%) are less than 0 in TE dimension, which is reflected in the deterioration of technical efficiency. Labor-intensive industries (3.397%), capital-intensive industries (4.541%), and technology intensive industries (6.539%) are all greater than 0 in the TP dimension, and technological progress is the core driving force. Based on the changes of TE and TP indexes, it was found that the industry heterogeneity is obvious. The greening process of technology-intensive industries includes both the improvement of technical efficiency and the role of technological progress. However, the green growth of labor-intensive and capital-intensive industries is more driven by the core of technological progress, and innovation is the main source of its future development.

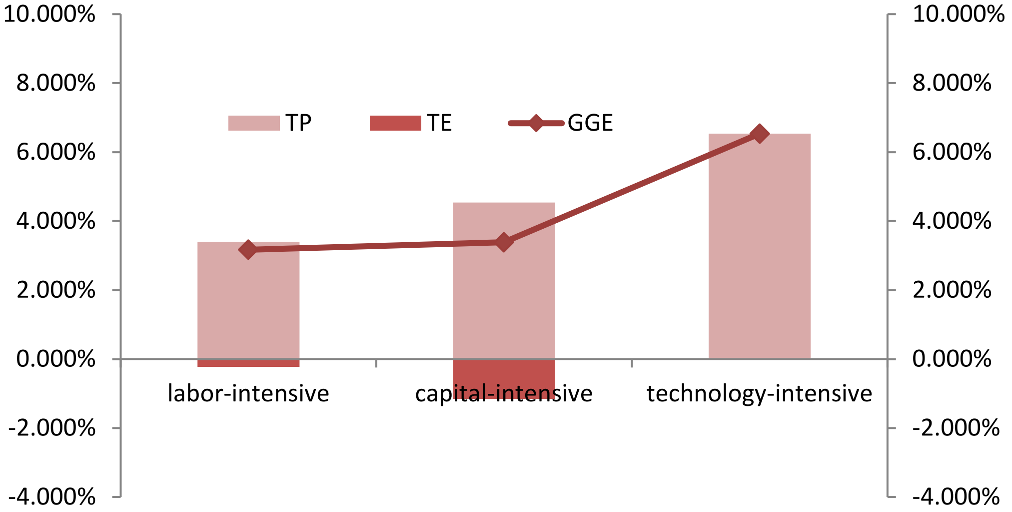


Figure 5. The results of industry heterogeneity.

5. Conclusions and Suggestion

5.1. Conclusions

With the intensification of the contradiction between economic growth, resource depletion, and environmental pollution, it is urgent to transform China's economic development mode to achieve green growth. As a pillar industry of the economy, identifying the green growth of the manufacturing industry and exploring its driving forces are crucial to China's pursuit of high-quality development. This research investigates the sustainable features of 27 manufacturing industries throughout 2005–2017. The results are as follows.

More than 60% of the industries are experiencing gray growth, and the growth efficiency has an erratic increasing tendency. The manufacturing industry is still in the middle stage of green development and does not yet have a distinct trend. The efficiency of labor-intensive, capital-intensive, and technology-intensive sectors differs greatly from the standpoint of manufacturing industry heterogeneity. Industries that rely heavily on technology have taken the lead and have exhibited a clear increasing trend. Since 2011, the efficiency of green growth in labor- and capital-intensive businesses has started to drop. Industries that rely primarily on labor and capital to thrive are unable to meet the demands of the green economy. Technological innovation is the core driving force for manufacturing to achieve green growth. Wang also reveals the interesting new trend that the Chinese construction industry is shifting from a typical labor-intensive industry to a knowledge- and technology-intensive industry [40]. This also shows the importance of technological progress to the development of industries driven by different factors.

From the change in dynamic, it can be seen that the growth rate of GGE in 2005–2017 was 4.369%, the annual growth rate of TE was -0.49%, and the annual growth rate of TP was 4.86%. At present, the growth of green growth efficiency mainly depends on the pulling effect of technological dividends brought by technological progress, rather than the improvement of technical efficiency. Technology-intensive industries have made significant technological progress and improved technical efficiency. While in labor-intensive and capital-intensive industries, the technological progress has improved the overall efficiency, the TE of these two industries is deteriorating. In connection with EKC, it is clear that technology effects, rather than scale-related changes, are the main drivers of green growth in the manufacturing industry [41–43].

Our empirical study contributes to the ongoing literature in several ways. Firstly, by focusing on the decoupling of resources, environment, and economy, this paper, which is informed by the green growth theory, suggests that the key to green growth in manufacturing is to consume less resources and environmental costs to obtain maximum economic advantages. An efficiency measurement model, based on the production function with labor, capital, and energy as input factors, industrial output as desirable output, and pollution emissions fitted as environmental pollution indexes as undesirable outputs, is constructed to conduct green growth state analysis of manufacturing industry. Secondly, based on the deconstruction of dynamic efficiency, we broadened the pertinent aspects of EKC theory and discovered that achieving green growth required more of a driving influence from technological progress than an improvement in production efficiency. Thirdly, we discovered that there is a common focus on the significant role played by technological advancement in the course of industrial development by comparing previous research. The diverse effects of particular innovation paths on manufacturing enterprises will next be further examined.

5.2. Suggestion

Based on the results, we discovered the importance of technological progress in the green development of manufacturing industry and put forward some proposals and suggestions for the Chinese government and enterprises.

For the government: firstly, encourage the manufacturing industry to increase investment in independent innovation. Secondly, improve the relevant preferential policies, from the side, to protect the operation of independent research and development. Thirdly, a special industry–university–research investment fund can be created, and advocated resource integration between scientific research institutions, research institutes and manufacturing enterprises, can be created to carry out cooperation and exchanges. Finally, establish and improve the investment and financing system to provide a variety of financial support for enterprises in a period of rapid development.

For the enterprise: on the one hand, enterprises are encouraged to build research and development centers. Small and medium-sized innovative enterprises can gradually establish their own R&D and innovation teams through cooperation with scientific research institutes and large R&D centers. On the other hand, strengthen the protection of intellectual property rights to ensure the normal operation of the innovation system. One of the important R&D achievements of enterprises' independent innovation is the intellectual property rights, such as patent technology. Strengthening the construction of the intellectual property protection system and learning the laws and policies of intellectual property protection are the premises to ensure the normal development of manufacturing enterprises' R&D and innovation activities, and they are also the guarantee to reduce enterprises' repeated R&D.

However, there are some limitations that require further research in the future. Firstly, the measurement of green growth efficiency of the manufacturing industry and the excavation of driving force are only the first step of research, and further scientific research is needed to improve this research in the future. Secondly, the study found the important driving force of technological innovation, but the specific impact remains to be further explored. Thirdly, if data regarding enterprises can be acquired, future empirical research needs to include samplings at firm level.

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