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Regional Green Innovation Efficiency in High-End Manufacturing

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ABSTRACT

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Using regional panel data of the high-end manufacturing industry in China from 2011 to 2015, the authors use projection tracking and a stochastic frontier model to analyze regional green innovation efficiency and influencing factors. Research shows that the innovation efficiency national average in high-end manufacturing is between 0.7 and 0.8 and that regional green innovation efficiency is polarized, presenting as high in the east and low in the west. Both of these measures illustrate some room for green innovation improvement. The number of research and development institutions and industry agglomeration have a significant positive influence on green innovation, while government funding plays a supporting role. Environmental regulation, market maturity, and degree of openness to the outside world have some negative effects on green innovation, with environmental regulation having significant effects. This paper provides evidence for the improvement of green innovation efficiency in the high-end manufacturing industry in China.

ADDITIONAL INDEX WORDS: *High end manufacturing, green innovation, efficiency, projection tracking, stochastic frontier.*

INTRODUCTION

Background and Research Significance

On 8 May 2015, China's State Council issued its first 10-year national plan, titled "Made in China 2025," for advancing China's manufacturing strategy toward "innovation-driven, quality-first, green development, structural optimization, and talent-oriented" basic principles. China's "13th five-year" plan also points out that innovation should be firmly established with coordinated, green, open, and shared development concepts. High-end manufacturing is the key indicator of national and regional competitiveness and is the key determinant of the global value chain. With the deep integration of a new generation of information technology and manufacturing industries, new modes of production, industry patterns, business models, and economic growth points are gradually formed. Developed countries, represented by the United States, Germany, and Japan, implement a "reindustrialization" strategy and have refocused their national economic priorities on manufacturing. High-end manufacturing is not only the key to maintaining world leadership in developed countries, but also the focus of these countries' development. A low-carbon green economy has also become a vital way for countries to transform economic development and realize the transition from a pattern of extensive economic growth to a pattern of green-intensive economic growth. "Made in China 2025" puts forward the "high-end equipment innovation project," pushing traditional industries to move from low-end manufacturing to the mid to high end. China's "13th five-year" plan focuses on high-end equipment manufacturing, emphasizing innovation-driven development of green and intelligent manufacturing.

China's high-end manufacturing industry is characterized by a large but weak self-dependent innovation capacity and low added value. From 2006 to 2015, business income in the high-end manufacturing industry quadrupled, with the sales of new products rising nearly 258%. The export scale of high-end manufacturing in China has been expanding, resulting in a trade surplus. However, in 2015, China's high-end manufacturing trade exports accounted for 63% of total exports, and general trade exports only 22.8% of total exports, which indicates that high-end manufacturing export products are the result of product processing and assembly, with a lack of independent research and development (R&D) products. In high-end manufacturing technology, foreign expenditure was $6.3 billion, whereas domestic expenditure was only $5.1 billion, so most technology relies heavily on the international market. The extensive economic growth mode no longer meets the needs of development in China and comes with the progressive loss of resources and environmental pollution. Therefore, it is of great significance to measure and evaluate the heterogeneity of green innovation efficiency and to explore the impact factor of high-end manufacturing in China and the provinces.

China's "13th five-year" plan specifies 10 key areas of high-end equipment manufacturing; however, because of the difficulty of data acquisition, this paper considers six high-tech manufacturing industries: medicine; aviation and spacecraft; electronics and communications; computer and office; medical instruments; and instrumentation.

Research Review

With the gradual weakening of environmental carrying capacity, the international community has become more

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concerned about the ecological environment, and green innovation has become the research focus of scholars. Kemp, Arundel, and Smith (1998) define green innovation as a new process technology, system, and product to avoid or reduce environmental damage. Brawn and Wield (1994) were the first to propose the concept of green technology, pointing out that it should include pollution control, recycling technology, ecological processes, purification technology, inspection and assessment technology, and so on. Compared with traditional technology innovation, which sacrifices resources and the environment in pure pursuit of economic efficiency, green technology has more significance to sustainable development.

A great deal of literature has explored the efficiency and influencing factors of green innovation: Ren, Niu, and Niu (2014) have built a green innovation efficiency model reflecting green development and innovation-driven concepts based on the Data Envelopment Analysis range-adjusted measure (DEA-RAM). Feng (2013) introduced the DEA–Slacks-based measure (DEA-SBM) model to measure the green technology innovation efficiency of Chinese industrial enterprises. Zhang and Zhu (2012) measured the green growth index of 36 industries in China with a SBM–directional distance function (SBM-DDF). Liu (2017) used the comprehensive evaluation model of principal component analysis and the four-stage DEA, which excludes external environment factors, to analyze the green technology innovation efficiency of industrial enterprises in China. Cao and Yu (2015), with a green and low-carbon perspective, used projection pursuit–stochastic frontier analysis (PP-SFA) to measure the green innovation efficiency of Chinese provinces. At the same time, many scholars have explored the factors of influence in green technology innovation efficiency. Liu and Huang (2017) studied the influence of foreign direct investment (FDI) entry mode on regional green technology innovation efficiency based on the perspective of environmental regulation. Bi, Jiang, and Li (2009) studied the technological transformation effect of multinational companies on green innovation performance and the effect of innovative resource investment on green system innovation, respectively. Zhang (2015) believed that domestic technology is more influential than FDI in China's industrial green growth.

At present, China's research on green technology innovation efficiency in the high-end manufacturing industry is relatively deficient. Huang, Zhang, and Yang (2016), on the basis of MDM-SIM, built a high-end manufacturing innovation index, with energy consumption per unit of industrial added value and carbon dioxide emissions as important evaluation indexes of innovation and high-end manufacturing in Beijing. Yu and Xu (2017) used the SFA model, based on the data of 30 provinces and cities in China, to measure the innovation performance of high-end equipment manufacturing and discussed its spatial agglomeration. He and Pan (2016) constructed an evaluation index system for technological innovation ability and applied it to the six kinds of high-end equipment manufacturing industries in China. Feng (2013) studied the innovation efficiency of China's high-tech industry based on the new perspective of a resource-constrained two-stage DEA model. On the basis of empirical data from high-tech industries, Wang and Wang (2016) studied the heterogeneity threshold effect of R&D investment on green innovation efficiency, and a small number of scholars have studied the influence factors of industry innovation efficiency. Dai and Liu (2016) empirically tested the relationship between market distortion and innovation efficiency in China's high-tech industry. Xiao, Li, and Zhongwei (2012) empirically demonstrated the overall efficiency of innovation in China's regional high-tech industries from a value chain perspective and pointed out that government support and the financial environment have a significant effect on overall innovation efficiency.

The above research provides a significant reference for the study of green innovation efficiency in high-end manufacturing industries, in view of the low amount of research in that field. This paper will expand on the following two aspects: (1) Overcoming the shortage of DEA and SFA assessments of innovation efficiency, the PP (Jin *et al*., 2004) and improved SFA (Bai, Jiang, and Li, 2009; Deja *et al*., 2017) are used to measure the green innovation efficiency of high-end manufacturing in China's provincial regions. (2) A panel data model is established based on provincial heterogeneity to focus on government funding, R&D institutions, environmental regulation, market maturity, industry concentration, and the degree of openness to foreign investment on the effect on technical efficiency, so as to explore a new path of green innovation and development of advanced manufacturing modes and to provide experience and reference.

METHODS

Index System and Data Selection

Index System

Input Indicators. Research and development activities are the basis for independent innovation in high-end manufacturing. Most studies have used the full-time equivalent of R&D personnel and funding inputs. Because of the particularity of high-end manufacturing, the main mode of independent innovation in most enterprises is the introduction and absorption of technology (Guan and Chen, 2010; Hansen and Birkinshaw, 2007). Feng and Teng (2010) considered that investment in high-tech industry R&D should include the introduction and absorption of technical funds. In this paper, R&D and technology expenditures and the cost of technology absorption are the input indexes of R&D funds.

Output Indicators. Considering the difference between green innovation output and general innovation activity output, output indicators should cover not only the general innovation output index, but also environmental and energy measures; therefore, green innovation efficiency should include innovation efficiency, economic efficiency, and green efficiency, The invention patent is the direct result of R&D activity and an indicator of scientific and technological innovation internationally; therefore, this paper uses the number of patent applications as an innovation output index of high-end equipment manufacturing (Guan and Gao, 2009). The ultimate value of scientific and technological innovation is its commercial value, and market acceptability directly reflects this value; therefore, this paper selects new product sales revenue and new product exports to compose the economic output index of high-end manufacturing. Many scholars consider energy consumption yield and environmental pollution from the perspective of green environmental protection; of the two, environmental pollution is a comprehensive index. This paper uses the discharge of waste water, waste gas, and solid waste for the comprehensive measurement of the environment pollution index (Korhonen and Luptacik, 2004). Because the environmental pollution index has a negative output, only by reducing the environmental pollution index can innovation efficiency improve; therefore, consulting previous studies, this paper uses the environmental pollution index as the output index of innovation.

Factors of Influence. Many factors influence the efficiency of technological innovation, but to study the efficiency of green technology innovation in high-end equipment manufacturing, not only innovation, but also environmental factors and government functions should be considered. A good deal of research has been toward the influence factors of green innovation efficiency. On the basis of previous studies, this paper selects government funding, market maturity, R&D institutions, industry concentration, environmental regulation, and the degree of openness to foreign participation to analyze the effect of green innovation efficiency on high-end manufacturing in provinces and autonomous regions throughout China, with the hope of finding a way to improve the innovation efficiency of high-end manufacturing in China's provinces.

(1) Government funding. Government funding plays an irreplaceable role in regional technology innovation of high-end manufacturing, but academic circles have different opinions on the role of government funding in the green innovation efficiency of these industries. Guan and Gao (2009) showed that business capital has a positive effect on the improvement of innovation efficiency in high-tech industries, whereas government funds are significantly negatively correlated with innovation efficiency. Yu (2009) believed that government support and financial support have a significant positive effect on the R&D efficiency of high-tech industries, with, however, significant differences in the effect of different government inputs on enterprise innovation. Different stages of development, different government funding methods, and different measurement efficiency methods may lead to inconsistent research results. In this paper, government R&D funds account for the government's fiscal expenditure in high-end manufacturing and is used to express government funding.

(2) Market maturity. The flow and optimization of knowledge and technology can be realized through the technology trading platform, namely, the market. Generally speaking, technology market maturity will have a corresponding effect on the innovation activity of the high-end manufacturing industry. The higher the maturity of the regional technology market, the easier it is to achieve technology diffusion. Both the provider and the demander side of the technology will see a certain boost. Gu and Lundvall (2006) believed that communication and cooperation between the technical supplier and the demand side has an important influence on improving the technical utilization rate and the conversion rate of scientific and technological achievements. Therefore, many places have built up the technical market. Because of the difficulty of obtaining maturity data for the high-end manufacturing technology market, in this paper, the ratio of the technology market turnover to the gross regional product in each province is used.

(3) Number of R&D institutions. Zhang, Zhao, and Chen (2014) argued that external R&D agencies connect to the cross-boundary search of technical knowledge and market knowledge. The cross-boundary search of these two kinds of knowledge, in turn, enhances enterprise innovation. In an increasingly competitive environment, it is difficult to meet the need for sustained innovation by just relying on the internal organization. Companies are increasingly relying on an open model to obtain innovative knowledge from external organizations and actively make up for the deficiency of internal knowledge. The more independent the R&D institutions in the region are to provide more technical exchanges for regional high-end manufacturing innovation activities, the more likely they are to produce technical spillover effects that are more conducive to the improvement of green innovation efficiency for high-end manufacturing enterprises.

(4) Industry concentration. Schumpeter (2006) argues that monopoly is closely related to R&D efficiency; the higher the market concentration, the better the incentive for enterprises to engage in R&D activities to obtain monopoly profits. Arrow (1962) challenged the idea that monopolies could foster efficiency in R&D, arguing that a competitive environment could give more incentive to R&D. Wang and Wang (2016) investigated the effect of industrial agglomeration on the efficiency of industrial green innovation using the space meter method. The results showed that industrial agglomeration has a significant effect on the efficiency of industrial green innovation. From previous studies, most scholars support Arrow's view. This paper argues that an increase in the number of regions and high-end manufacturing enterprises promotes interindustry and intraindustry technology spillover and enhances enterprise competitiveness, so as to realize scientific and technological innovation efficiency.

(5) Environmental regulation intensity. Environmental regulation has an important effect on the innovation activities of high-end manufacturing industries. Some scholars, influenced by classical economic theory, believe that environmental regulation increases the investment in prevention and treatment of pollution, squeezes out capital, weakens technological innovation, and negatively affects innovation efficiency (Grey, 2003; Li, Han, and Wei, 2018). Then, Porter and scholars who support the Porter hypothesis show that the strength of environmental regulation can motivate enterprises to effect technology innovation, reducing or even offsetting environmental regulation costs and improving the efficiency of innovation. In terms of environmental regulation measures, some scholars proceed from the perspective of energy sources, and others from the perspective of environmental governance. In this paper, energy consumption has been used as an important indicator of green innovation efficiency in high-end manufacturing industries. Therefore, an investment in environmental pollution control is used to represent the strength of environmental regulation.

(6) Degree of openness. The sustainable development of high-end manufacturing depends on the international market, and

the degree of openness in a country determines the international market technology spillover intensity to a certain extent. A number of factors influence technology innovation in high-end manufacturing in China. Attracting FDI in an open environment is an effective way for China's provinces to obtain foreign advanced technology spillover and is helpful in improving the efficiency of green technology innovation in the high-end manufacturing industry (Han, 2012). In this paper, the ratio of the to introduce technology expenditure and the gross regional product in each province is indicated.

Data Selection

Data Collection. The data are mainly from the 2012–16 China Statistical Yearbook on Science and Technology, China Statistical Yearbook, and China Environment Statistical Yearbook. Because of a lack of data, Tibet, Yunnan, Hainan, and Xinjiang provinces have been abandoned. Based on 2011–15 data from 27 of China's provinces and autonomous regions, the evaluation of China's provincial high-end manufacturing green innovation efficiency, as well as the six factors of influence described above, were analyzed.

Data Processing. For the two types of data, income and cost, different dimensionless methods are taken to eliminate the dimensional difference between the original data and the resulting analysis result error.

The nondimensional formula of income type is:

$$X(i,j)_t = \frac{x(i,j)_t - x_{\min}(j)_t}{x_{\max}(j)_t - x_{\min}(j)_t} \quad (1)$$

The nondimensional formula of cost type is:

$$X(i,j)_t = \frac{x_{\max}(j)_t - x(i,j)_t}{x_{\max}(j)_t - x_{\min}(j)_t} \quad (2)$$

In Equations (1) and (2), $x(i,j)_t$ represents the jth index value of the ith region of the tth year (where $t = 1, 2, \ldots, 5$; $i = 1, 2, \ldots, 27$; and $j = 1, 2, \ldots, 15$); $x_{\max}(j)_t$ and $x_{\min}(j)_t$ represent the maximum and minimum values, respectively, of the jth variable of the 27 provinces and autonomous regions in year t; and $x(i,j)$ represents the dimensionless variable. Because the data can be zero, the coordinates are translated to eliminate its effect (Meng and Li, 2012; Liu, 2017):

$$y(i,j)_t = X(i,j)_t + A \quad (3)$$

where, the index value of the dimensionless data is shifted, which is the amplitude of translation. Because of the length of the article, no dimensionless data is shown.

Modeling

Model Solution Framework. The high-end manufacturing green innovation index involved three input and four output variables, which means the traditional SFA, which can only measure one innovation activity output, is not suitable for this research. Instead, it is necessary to transform the multidimensional index into one dimension by dimension reduction technology. Based on the PP method, this paper analyzes the green innovation efficiency and influencing factors of the high-end manufacturing industry, and on this basis, the logarithmic SFA model is adopted.

Projection Pursuit Model. The PP can reduce multidimensional data to one-dimensional data by determining the projection direction according to the data structure characteristics. The environmental pollution index and the innovation output of this paper use projection tracking to reduce dimensions. The environmental pollution index comprises effluent discharge, exhaust emission, and solid waste discharge. Meanwhile, the innovation output comprises patent application, new product sales revenue, comprehensive energy consumption output rate, and new product exports. With the environmental pollution index as an example, the following steps are taken (Fu and Zhao, 2006):

(1) Calculate the environmental pollution projection value: In Equation (4):

$$z(i)_t = \sum_{j=1}^{p} a(j)_t y(i,j)_t \quad (4)$$

where, $a(j)_t$ represents the projection direction of the jth variable ($j = 1, 2, 3$) at year t, and $z(i)_t$ is the environmental pollution projection value.

(2) Construct the projection exponential function:

$$Q(a) = S_z D_z \quad (5)$$

where, S_z is the standard deviation of $z(i)$, and D_z is the local density of $z(i)$.

(3) Optimize the projection index function. When the sample set is timed, the projection index function only changes with the projection direction. To construct the complex nonlinear optimization function, the optimal projection direction and maximum function value of the projection index function are optimized by the accelerated genetic algorithm:

$$\begin{cases} \max Q(a_t) = S_z D_z \\ \text{s.t.} \sum_{j=1}^{3} a^2(j)_t = 1 \end{cases} \quad (6)$$

(4) Calculate the environmental pollution index. The optimal projection direction a_t^* of the "three wastes" variable obtained from step (3) is substituted into Equation (4) to obtain the environmental pollution projection value $z(i)_t$, that is, the environmental pollution index.

The four green innovation output variables for the high-end manufacturing industry can also be calculated in the above steps of the PP model to calculate the comprehensive green innovation index, which will not be repeated here.

Stochastic Frontier Approach. The SFA is a stochastic boundary model with a complex perturbation term (Figure 1). The advantage, compared with DEA, is that it can not only measure the technical efficiency, but also analyze the ineffective factors of various disturbances, namely influencing factors (Li and Mu, 2013). In this paper, the logarithmic production function is used to measure the innovation efficiency, which is different from the Cobb–Douglas production function. The logarithmic production function is more flexible in form and can avoid the estimation error from improper model setting. The stochastic frontier model used in this paper is a logarithmic production function as follows:

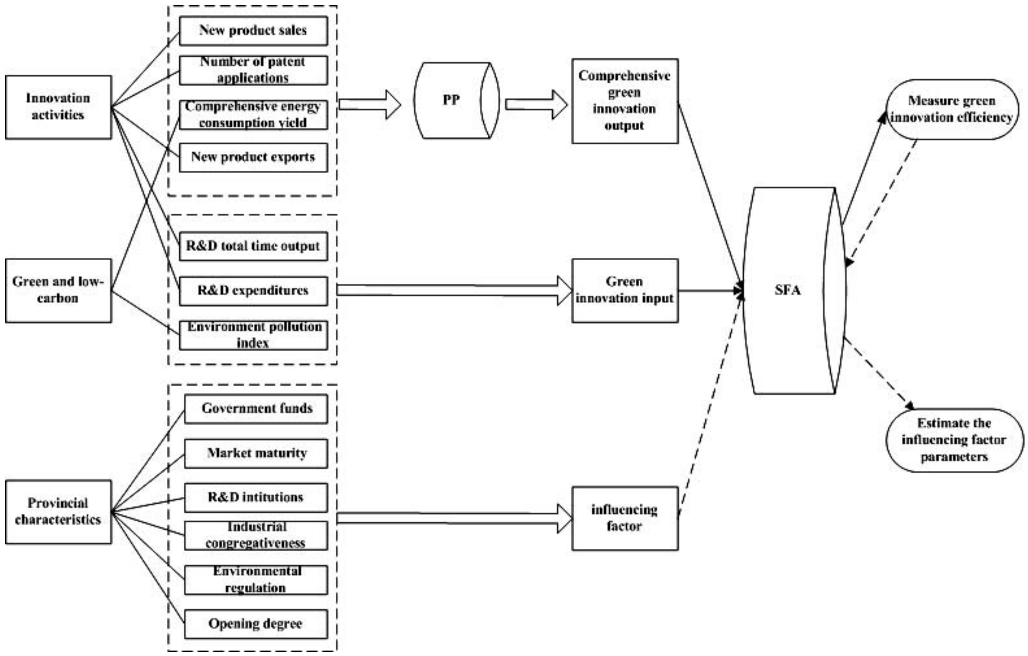

Figure 1. Measurement model of green innovation efficiency in manufacturing.

$$\ln y_{it} = \beta_0 + \beta_1 \ln l_{it} + \beta_2 \ln k_{it} + \beta_3 \ln p_{it} + \beta_4 (\ln l_{it})^2 + \beta_5 (\ln k_{it})^2 + \beta_6 (\ln p_{it})^2 + \beta_7 \ln l_{it} \ln k_{it} + \beta_8 \ln l_{it} \ln p_{it} + \beta_9 \ln k_{it} \ln p_{it} + v_{it} - u_{it} \quad (7)$$

where, y_{it} represents the comprehensive green innovation output value of the ith region at year t; l_{it} represents full-time equivalent R&D staff, k_{it} is R&D funding, and p_{it} is the environmental pollution index; the β_i are the parameters to be estimated, and $v_{it} - u_{it}$ is the error term, where v_{it} are random variables $v_{it} \sim N(0, \sigma^2)$ and are assumed to be independent and u_{it} are nonnegative random variables, assuming $u_{it} \sim N(m_{it}, \sigma^2)$ is the half of the truncated distribution that reflects production technology inefficiency (*i.e.* the high-end manufacturing industry green technology efficiency loss in ith region at year t).

Based on the stochastic frontier production model, this paper introduces the technology inefficiency function to analyze further the influence of the six factors (*e.g.*, government subsidy, market maturity, R&D institutions, degree of industrial agglomeration, environmental regulation, and degree of openness) on green innovation efficiency of the high-end manufacturing industry:

$$m_{it} = \delta_0 + \delta_1 \mathrm{GOV} + \delta_2 \mathrm{TMM} + \delta_3 \mathrm{RDI} + \delta_4 \mathrm{IAD} + \delta_5 \mathrm{ER} + \delta_6 \mathrm{OPEN} \quad (8)$$

where, m_{it} is the average value of the technology inefficiency item in green innovation output, GOV represents government subsidy, TMM is market maturity, RDI is the number of R&D institutions, IAD is industry concentration, ER is environmental regulation, and OPEN is the degree of openness.

RESULTS

Calculation of Environmental Pollution Index

The environmental pollution index of the high-end manufacturing industry in 27 provinces and autonomous regions in China from 2011 to 2015 was estimated comprehensively with Matlab R2014a software according to the PP model with the best projection direction of waste water, waste gas, and solid waste (see Table 1).

The best projection direction of the "three wastes" in each year was then used to calculate the projection value of environmental pollution by Equation (4) (*i.e.* the environmental pollution index; Table 2).

Estimation of Green Innovation Output Index

The best projection direction of the number of patent applications, new product sales revenue, comprehensive energy consumption output rate, and new product exports of the high-end manufacturing green innovation was calculated comprehensively with Matlab R2014a software according to the PP model, and Equation (4) was used to calculate the regional high-end manufacturing green innovation output projection values (Table 3). Because of space constraints, the best projection direction of green innovation output is not explained.

Table 1. *Best projection direction of the "three wastes."*

Environmental Pollution Index Variable	Projection Direction				
	2011	2012	2013	2014	2015
Waste water discharge	0.5462	0.7106	0.0086	0.4924	0.6178
Exhaust emission	0.3506	0.4474	0.8165	0.2957	0.2378
Solid waste emissions	0.7607	0.5431	0.5772	0.8186	0.7495

Table 2. *Environmental pollution index.*

Region	Environmental Pollution 2011	2012	2013	2014	2015
Beijing	0.0100	0.0100	0.0100	0.0100	0.0100
Tianjin	0.0765	0.0897	0.0793	0.0956	0.0838
Hebei	1.4798	1.4874	0.9842	1.4712	1.4798
Shanxi	0.7768	0.8270	0.4518	0.8059	0.9037
Inner Mongolia	0.5997	0.6374	0.3302	0.7077	0.8270
Liaoning	0.7511	0.8237	0.4785	0.8323	0.9684
Jilin	0.1726	0.1977	0.1858	0.1767	0.1977
Heilongjiang	0.1811	0.2507	0.2123	0.2241	0.2357
Shanghai	0.1722	0.1860	0.2231	0.1851	0.1677
Jiangsu	0.9331	0.9857	1.1814	1.0887	0.9684
Zhejiang	0.5176	0.5660	0.7669	0.5410	0.4758
Anhui	0.4987	0.5213	0.4387	0.5372	0.5767
Fujian	0.4068	0.4040	0.4753	0.3716	0.3195
Jiangxi	0.3482	0.3834	0.3303	0.3546	0.4045
Shandong	0.9823	0.9850	1.0103	1.0613	1.0957
Henan	0.7470	0.7564	0.7423	0.7957	0.7316
Shanxi	0.4210	0.4135	0.4283	0.4182	0.4218
Hunan	0.3578	0.4019	0.4357	0.3393	0.3227
Guangdong	0.5997	0.6374	0.8231	0.6307	0.5499
Guangxi	0.4878	0.5251	0.4562	0.3691	0.3181
Chongqing	0.1190	0.1274	0.1478	0.1413	0.1423
Sichuan	0.4523	0.4802	0.3498	0.4525	0.4211
Guizhou	0.1707	0.2388	0.2223	0.3547	0.2936
Yunnan	0.4021	0.4135	0.2321	0.3743	0.4121
Shanxi	0.2458	0.2616	0.2058	0.2966	0.3346
Gansu	0.1776	0.2084	0.1211	0.1908	0.2092
Ningxia	0.1076	0.1053	0.0744	0.1358	0.1183

Table 3. *High-end manufacturing innovation output projection value.*

Region	High-End Manufacturing Innovation 2011	2012	2013	2014	2015
Beijing	0.2881	0.3017	0.4925	0.2457	0.2012
Tianjin	0.1581	0.2017	0.4128	0.1785	0.1494
Hebei	0.0278	0.0410	0.0978	0.0379	0.0345
Shanxi	0.0262	0.0411	0.1389	0.0161	0.0064
Inner Mongolia	0.0222	0.0399	0.1765	0.0130	0.0038
Liaoning	0.0805	0.0900	0.2284	0.0651	0.0538
Jilin	0.0343	0.0511	0.2165	0.0284	0.0132
Heilongjiang	0.0398	0.0555	0.2308	0.0333	0.0189
Shanghai	0.2147	0.2070	0.4125	0.1784	0.1584
Jiangsu	0.7779	0.8048	0.7935	0.7723	0.7813
Zhejiang	0.2583	0.2972	0.4941	0.2951	0.3341
Anhui	0.0812	0.1084	0.2437	0.1075	0.1271
Fujian	0.1794	0.1966	0.3361	0.1437	0.1375
Jiangxi	0.0495	0.0707	0.2472	0.0600	0.0576
Shandong	0.2514	0.2570	0.2308	0.2439	0.3120
Henan	0.0460	0.0610	0.2472	0.1806	0.2058
Shanxi	0.0718	0.0920	0.2227	0.0946	0.1042
Hunan	0.0829	0.0921	0.2604	0.1071	0.1172
Guangdong	1.4191	1.4184	1.5027	1.4224	1.4119
Guangxi	0.0324	0.0476	0.2106	0.0230	0.0111
Chongqing	0.0785	0.0709	0.2478	0.0617	0.1128
Sichuan	0.1121	0.1449	0.2540	0.1591	0.1478
Guizhou	0.0343	0.0552	0.2347	0.0379	0.0211
Yunnan	0.0326	0.0475	0.2049	0.0206	0.0076
Shanxi	0.0672	0.0780	0.2388	0.0569	0.0484
Gansu	0.0331	0.0511	0.2459	0.0210	0.0067
Ningxia	0.0326	0.0491	0.2471	0.0166	0.0045

Green Innovation Efficiency Measurement

The comprehensive green innovation output value and the environmental pollution index were estimated by the PP method, and both were substituted into the SFA model to measure province high-end manufacturing green innovation efficiency from 2011 to 2015 and analyze government subsidy and market maturity effect factors on the efficiency of green innovation (see Table 4).

Table 4 shows that $\gamma = 0.946$, which is significant at the 5% level, indicating that the SFA method is suitable. The logarithmic likelihood function value is 9.68, which indicates that the maximum likelihood estimation is better. The unilateral likelihood ratio (LR) test value is 55.65, indicating the overall estimation is effective. In the production function section, the effect of R&D personnel in promoting innovation is shown to be significant, further verifying that talent plays a pivotal role in innovation activities. Table 4 shows that the average green efficiency from 2011 and 2015 is 0.781, which indicates that China's high-end manufacturing industry has made great progress in green innovation activities, but with some inefficiencies.

DISCUSSION

This paper analyzes the effect of six aspects on green innovation efficiency in the high-end manufacturing industry of China's provinces and autonomous regions: government subsidy, market maturity, R&D institutions, degree of industrial agglomeration, environmental regulation, and degree of openness to the outside world. The estimated coefficients and t test values in Table 4 show the direction and extent of the influencing factors.

Government funding, R&D institutions, and industrial agglomeration have a positive effect on the green innovation efficiency of China's high-end manufacturing industry. The number of R&D institutions and the degree of industrial aggregation have significant positive effects on green innovation efficiency at the 1% and 5% levels, respectively. The greater the number of institutions, the higher the degree of industrial agglomeration and the more effective the improve-

Table 4. *Estimation results of the stochastic frontier production function and efficiency function.*

Variable	Estimated Coefficient	t Value
Production function constant item	0.622^{***}	9.734
$\ln l_{it}(\beta_1)$	0.836^{***}	3.862
$\ln k_{it}(\beta_2)$	0.116	0.518
$\ln p_{it}(\beta_3)$	0.014	0.289
$(\ln l_{it})^2(\beta_4)$	0.533^{*}	1.710
$(\ln k_{it})^2(\beta_5)$	0.266	1.356
$(\ln p_{it})^2(\beta_6)$	0.005	0.392
$\ln l_{it} \ln k_{it}(\beta_7)$	-0.217^{*}	−1.863
$\ln l_{it} \ln p_{it}(\beta_8)$	−0.045	−0.411
$\ln k_{it} \ln p_{it}(\beta_9)$	−0.18	−0.806
GOV(σ_1)	−0.138	−1.530
TMM(σ_2)	0.217	1.481
RDI(σ_3)	-0.284^{***}	−2.977
LAD(σ_4)	-0.217^{*}	−1.932
ER(σ_5)	0.595^{***}	3.344
OPEN(σ_7)	0.017	0.340
σ^2	0.217^{***}	3.511
γ	0.946^{***}	25.834
Logarithmic likelihood function value	9.676	—
LR test of the one-sided error	55.652	—
The mean of green innovation efficiency	0.781	—

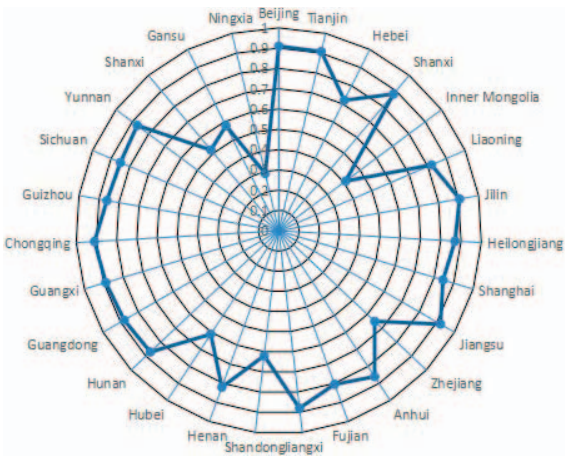

Figure 2. Average green innovation efficiency in high-end manufacturing in different regions of China.

ment of green technology innovation efficiency in China's high-end manufacturing industry. The government subsidy is only an auxiliary means for the output of innovation activities (Li and Mu, 2013).

Market maturity, environmental regulation, and openness to the outside world have a negative effect on the green innovation efficiency of China's high-end manufacturing industry, and the effects of environmental regulation are more significant at the 1% level, indicating that environmental regulation has a significant negative effect on high-end manufacturing green innovation. In the early days of environmental governance, a large amount of money is needed to deal with the problem of environmental pollution, which leads to an increase in the cost of governance, thus affecting the improvement of green innovation efficiency to a certain extent. Openness is characterized by foreign R&D funds in China's regional high-end manufacturing industries. The entry of foreign funds has a technology spillover effect on the region that leads to a degree of overreliance on foreign advanced technology, thus curbing the driving force of independent R&D, which is not conducive to high-end manufacturing green innovation efficiency.

Regional Heterogeneity Analysis of Green Innovation Efficiency in High-End Manufacturing Industry

The differences in the average green innovation efficiency of China's regional high-end manufacturing industry are significant. Regional development is not balanced, showing "east high, west low" results (Figure 2).

From region to region, efficiency levels show a large differences. The average green innovation efficiency of the top five areas are located in the eastern region, and green innovation efficiency ranking of the five areas are almost all in the midwest and west (Mi *et al*., 2016). The average green innovation efficiency of high-end manufacturing in Jiangsu, Beijing, and Tianjin is higher, among the forefront, because of strengths in economic and scientific research, coupled with the growing ecological environment in recent years in these three

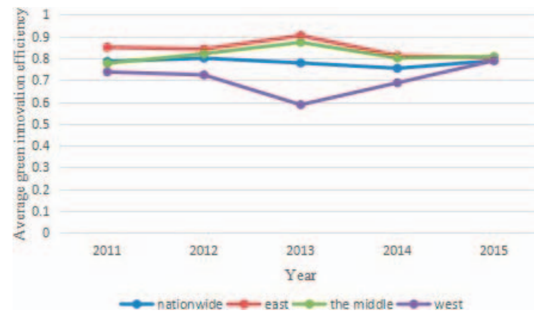

Figure 3. Average green innovation efficiency in high-end manufacturing of the three big regions of China from 2011 to 2015.

regions, and active promotion of resource development, intensive use, energy savings, and sustainable development (Figure 3).

Ningxia, Inner Mongolia, and Shanxi regions of the high-end manufacturing industry average green technology innovation efficiency ranking three. Ningxia and Shanxi are located in remote areas and have a low level of economic development. Furthermore, the facilities for institutions of high-end manufacturing industry are lacking. The low green innovation efficiency in Inner Mongolia comes from a reliance on the rich coal resources. Economic development depends on developing coal resources as the main factor for extensive economic growth, so that resource and environmental capacity is abated, causing a relatively low level of green innovation efficiency. Additionally, it is generally believed that green technology innovation efficiency in some regions in this study, such as Zhejiang, should be high. The average green innovation efficiency of Zhejiang is low, however, which is seriously inconsistent with its level of economic development. Most industry in Zhejiang province is chemical fiber, textile, and other light industry, and high-end manufacturing accounts for a lower proportion of industrial gross output, thus leading to a low level of the green technology innovation efficiency.

CONCLUSIONS

This paper uses the panel data of 27 provinces and municipalities in China during 2011–2015 to measure the green innovation efficiency of high-end manufacturing in each region, combining PP and SFA to analyze the regional heterogeneity of green innovation efficiency. At the same time, the influence of four factors on green innovation efficiency in the high-end manufacturing industry is discussed in terms of government funding, market maturity, R&D institutions, industrial concentration, intensity of environmental regulation, and degree of openness to the world.

High-end manufacturing, which is a key area in the global industrial chain and the high end of the value chain, is the strategic industry in China since the "13th five-year" plan. The analysis of green innovation efficiency and its influencing factors for high-end manufacturing in China brings to light three points on the road to ecological development: First, both the economically developed eastern areas and the less developed central and western regions must, from the perspective of a long-term development strategy, adhere to green development, use sustainable development as an important focus of building manufacturing power, develop a circular economy, and build a green manufacturing system. Second, the introduction of foreign advanced technology must not overcome domestic efforts, stifling independent innovation, which must be the basis for the development of green science and technology innovation in high-end manufacturing. Third, the talents of fundamental building and manufacturing power should lead the development path.

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