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RESEARCH ARTICLE

Investigating the development efficiency of the green economy in China's equipment manufacturing industry

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Abstract

The equipment manufacturing industry is the industrial base of China, which makes it imperative to coordinate the relationship between industrial development and environmental protection. Using panel data of the seven sub-industries in China's equipment manufacturing industry from 2011 to 2015, this paper evaluates the static and dynamic aspects of green economic development efficiency by combining the super-efficiency slack-based measure model of unexpected output and the data envelopment analysis-Malmquist index model. The results show investments in research and development, and environmental regulations have yielded some positive results, but that regulations have also yielded some undesired output in terms of diminished economic benefits. Pure technical efficiency and scale efficiency have both declined, indicating that the scale and industrial structure need to be further optimized. The results of this study present an objective and comprehensive assessment of green economic development of China's equipment manufacturing industry and provide valuable insights for improving green economic development efficiency.

Keywords Environmental regulation · Green economy · Equipment manufacturing industry · Super efficiency SBM · DEA Malmquist index

Introduction

As China enters the middle stage of industrialization, industries provide heightened economic benefits alongside significant environmental damage and serious ecological decline. According to the China Statistical Yearbook on Environmental (2018), China's total investment in environmental pollution control for 2017 was 953.9 billion Chinese Yuan (CNY) (1.15% of GDP), where roughly 7.14% of which, or about CNY 68.15 billion, was spent for industrial pollution control. The expenditure towards wastewater, waste gas, and solid waste (hereinafter referred to as three wastes) were CNY 7.64 billion, CNY 44.63 billion, and CNY 1.27 billion, respectively. Ecological environment protection is a real problem that the industry has to face in the process of development. The equipment manufacturing industry is an integral part of industrial development, also known as the industrial base, and is referred to as the backbone of the manufacturing industry. In 2017, the profit volume was CNY 2.671.332 billion, accounting for 35.66% of the industrial proportion. Its development degree has a significant impact on the economic benefits of the whole industry. However, along with the growth of the equipment manufacturing industry, the problem of pollution has also intensified. Given the intertwined and coupling relationship between the economy and the environment, countries all over the world have started redefining their long-term strategies in line with initiatives of the green economy. The green economy is aimed towards sustainable economic development without disregarding the need for environmental protection.

Previous studies have highlighted the importance of including the value of environmental protection and sustainable development in the economic decision and policy-making (Zhou 2017; Jerath et al. 2016; He et al. 2018). Kuosmanen et al. (2009) analyzed the impact of environmental policies on economic entities using cost-benefit analysis and found that environmental regulations have a temporal effect. In the short term, the positive effect of environmental policies on the economy is hardy perceivable and difficult to ascertain; but in the long term, economic benefits become more explicit and well-

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defined. In recent years, China has committed to green economic development, which has been identified as an essential goal of ecological civilization construction. One of China's primary industries that have been directly affected by green initiatives is the equipment manufacturing industry. However, there is a lack of research on the integration of environmental regulation, economic development, and technological innovation in the equipment manufacturing industry.

In this work, the development trends of the economic benefits and environmental pollution of China's equipment manufacturing industry were explored. The economic data for 2011–2015 were obtained from the China Environment Statistical Yearbook, China Industry Statistical Yearbook, and China Science and Technology Statistical Yearbook. To better understand the relationship between economic development and environmental protection, this study utilizes evaluation indicators of green economic benefits of China's equipment manufacturing industry from the economic, environmental, and science and technology dimensions. The super-efficiency SBM model and the Malmquist index method based on the DEA were used to provide both static and dynamic perspectives, determine the green economic development efficiency of China's equipment manufacturing industry, and identify the industries with low relative efficiency. The results of this research can be used in policymaking and planning for the manufacturing industry. The remainder of this paper is structured into the following sections. "Literature review" section presents an extensive review of the development of environmental regulation. Afterward, "Economic development, pollution discharge, and investment in science and technology of China's equipment manufacturing industry" section shows economic development, pollution discharge, and investment in the science and technology of China's equipment manufacturing industry. "Evaluation of green economic development efficiency of the equipment manufacturing industry in China" section provides the specific methodology of the assessment of the green economic development efficiency of the equipment manufacturing industry. "Results and discussion" section further discusses the application of the method presented in this work on China's equipment manufacturing industry for 2010–2015 in the seven sub-industries. Finally, "Conclusion" section concludes this paper.

Literature review

Environmental regulation and economic growth

At present, there are two main views regarding the relationship between environmental regulation and the economy. On the one hand, some believe that environmental regulations develop into additional burdens to enterprises and form into the "compliance cost." Such burden inhibits the production rate and profitability of enterprises and is detrimental to economic growth (Jaffe and Palmer 1997; Freeman et al. 1972; Stephens and Denison 1981; Brännlund et al. 1995; Wang et al. 2015). On the other hand, some have argued that environmental policies can improve productivity by stimulating the efficiency of technological innovation, thereby covering any additional cost brought by regulations (Porter and Claas 1995; Matthews 1981). Yang et al. (2012) verified the "innovation compensation effect" using industrial data from Taiwan. Telle and Larsson (2007) found a positive correlation between regulatory intensity and the total productivity of green industries. Wang et al. (2018) found that a higher intensity of environmental regulation can stimulate the development of the manufacturing industry, and the economy of different industries is more concentrated. These studies, among others, have shown the intertwined relationship of environmentalism and high-quality development, particularly in the equipment manufacturing industry.

Environmental regulation and technological innovation

Previous studies have found that environmental regulation has a significant positive correlation with environmental technology R&D (research and development) investment (Arimura and Sugino 2007; Lanoie et al. 2008; Wang et al. 2020). In terms of productivity, environmental regulation was found to have a negative correlation in the short term, and a positive correlation in the long term. They have concluded that the Porter hypothesis can be applicable to the pollution-intensive manufacturing industry in China. However, in the long run, environmental regulations can squeeze investments in R&D (Yuan and Xiang 2018). Testa et al. (2011) concluded that stricter environmental regulations provide a positive impetus in increasing investment in advanced technology equipment and innovative products and in improving enterprise performance. Telle and Larsson (2007) tested the relationship between the intensity of environmental regulation and the total factor productivity in Norwegian industries. They found that the higher the intensity of environmental regulation, the higher the total factor productivity. Magat (1978) concluded that technology innovation could push enterprises to solve environmental problems at the lowest cost and improve the profit margin through technology innovation behavior. In general, the relationship between environmental regulations and technological innovation in the equipment manufacturing industry exhibits a U-shaped feature, where a negative correlation exists in the short term and changes to positive in the long term.

Other factors could affect the relationship between environmentalism and technological innovation (Testa et al. 2011; Ramnathan et al. 2010). Noticeable differences regarding the impact of interregional environmental regulations on technological innovation can be observed in the equipment manufacturing industry in China. In particular, only in the eastern region do environmental regulations and technological innovation exhibit a U-shaped relationship. When Bos et al. (2013) analyzed the innovation mode of 21 European manufacturing enterprises, they found that along with the maturity of the industry, the degree of product innovation gradually decreased while the degree of process innovation gradually increased.

Heterogeneity of manufacturing industry, technological innovation, and environmental regulation

Several studies have found that the use of unified regulatory policies should be avoided due to the heterogeneity of the impact of environmental regulations on industrial technological innovation (Fortin 2005). Kang et al. (2018) recommend that China should increase R&D investments to improve the overall efficiency of the light industry since it has a stronger investment effect than the industry. Yuan et al. (2017) pointed out that in both high and low ecological environment, the impact of environmental regulation on technological innovation has an inverted U-shape, while the green economy has a U-shape. The technological innovation and environmental regulation in the middle ecological efficiency group are all U-shaped. For heavy pollution industries, the high intensity of environmental regulation weakens the technological innovation ability of enterprises. While for industries with only moderate pollution, environmental pollution control is relatively coordinated, and multiple regulatory measures should be used adaptably (Shen et al. 2019; Qin et al. 2020).

Economic development, pollution discharge, and investment in science and technology of China's equipment manufacturing industry

Economic benefit analysis of equipment manufacturing industry in China

Since China Environmental Statistics Yearbook no longer publishes the pollution emission data of the equipment manufacturing industry by industry, the Ministry of Environmental Protection revised the index system, investigation method, and relevant technical regulations. Considering the uniformity and availability of data statistical standards, this study has selected the data from 2011 to 2015 for analysis. The evaluation of economic benefits mainly comprises the output value of industrial sales and the total profit.

In the context of the entire industry, the industrial sales value of equipment manufacturing industry accounts for roughly a third of the whole industry (Tables 1 and 2). In 2011, the sales value of the equipment manufacturing sector accounted for 32.69% of the entire industry; and given its steady incline, the value reached 34.50% in 2015. The growth rate of the total industrial sales value of the equipment manufacturing industry reached 40.73%, which is higher than the growth rate of the entire industry at 33.37%. The total profit of the equipment manufacturing industry increased by 41.82%, which is much higher than the national industrial growth at 17.14%. These statistics highlight the importance of developing the equipment manufacturing industry in the growth of the national economy.

In terms of sub-industries, the industrial sales value of the transportation equipment and the computer, communication, and other electronic equipment manufacturing have an absolute advantage, with the two subindustries accounting for nearly 1/2 of the value of the entire industry. Profit from the transportation equipment manufacturing accounts for nearly 1/3 of the entire industrial profit, the highest among all subindustries. The total profit from the computer, communication, and other electronic equipment manufacturing increased by 79.32%, while profit from the general equipment manufacturing and special equipment manufacturing only increased by 4.05% and 5.83%, respectively. The data presented in Tables 1 and 2 suggest that the economic benefits of China's equipment manufacturing industry have steadily increased but that the growth rate has been slowing down, and the economic benefits (value and profit) vary significantly for the different industries.

Analysis of environmental regulation of China's equipment manufacturing industry

At present, main approaches used in measuring and evaluating environmental regulations are as follows: (1) number of environmental laws and regulations (Berman and Bui 2001), (2) the cost of pollution reduction (Gray and Shadbegian 2003), (3) emission reduction of pollution (Ramanathan et al. 2010) Similar to their research, the following equation is used in this study:

$$I_{\text{waste}} = D_{\text{waste}} / S_{\text{output}} \tag{1}$$

where I_{waste} is the waste discharge intensity (for either wastewater, exhaust gas, or solid waste); D_{waste} is the corresponding waste discharge; and S_{output} is the corresponding industrial sales output.

The impact of China's environmental regulations on the equipment manufacturing industry has become pronounced based on the statistical data (Table 3). The total industrial emissions of wastewater, waste gas, and solid waste have declined by 22.82%, 38.37%, and 18.21%, respectively. The emission intensity of wastewater in the metal products industry decreased by 31.86%, the emission intensity of waste gas in the special equipment manufacturing decreased by 75.77%, and the emission intensity of solid waste in general equipment

Table 1 Industrial sales value of China's equipment manufacturing industry from 2011 to 2015 (Unit: CNY 100 million)

Industry	2011	2012	2013	2014	2015	Rate of change
1	22,882.48	28,970.62	33,207.42	36,612.45	37,671.69	64.63%
2	39,992.18	37,813.12	43,314.80	47,150.91	47,172.70	17.95%
3	25,354.42	28,421.16	32,467.75	35,039.02	36,185.03	42.72%
4	62,256.41	66,172.62	75,377.38	84,995.92	90,161.26	44.82%
5	50,141.59	54,195.48	61,442.08	66,921.57	69,558.22	38.72%
6	62,567.28	69,480.88	78,318.64	85,274.75	91,378.86	46.05%
7	7444.16	6620.71	7521.52	8286.27	8749.31	17.53%
Total of equipment manufacturing industry	270,638.52	291,674.59	331,649.59	364,280.89	380,877.07	40.73%
National industry	827,796.99	909,797.17	1,019,405.3	1,092,197.99	1,104,026.70	33.37%
Proportion of equipment manufacturing industry in national industry	32.69%	32.06%	32.53%	33.35%	34.50%	

1-Metal products industry; 2-General equipment manufacturing; 3-Special equipment manufacturing industry; 4-Transportation equipment manufacturing industry; 5-Electrical machinery and equipment manufacturing industry; 6-Manufacturing of computer, communication and other electronic equipment; 7-Instrument manufacturing industry

manufacturing decreased by 40.04%. However, not all subindustries exhibited declines in their waste discharge intensities. For instance, the exhaust emission intensity of the instrument manufacturing increased by 122.39%, while its solid waste emission intensity increased by 43.70%. For electrical machinery manufacturing, while emission intensity from wastewater and solid waste decreased, the emission intensity of exhaust gas rose by 45.92%. This means that in later stages of development, the industry would need to strengthen its supervision and initiate additional measures to curb waste discharge in particular sub-industries.

An analysis of scientific and technological innovation in China's equipment manufacturing industry

The scientific and technological innovation is analyzed in terms of inputs of human, material, and financial resources to the equipment manufacturing industry, as well as outputs including the number of effective invention patents, new product sales revenue, and industrial sales output value. The summary of technological innovation inputs for 2011 and 2015 are shown in Table 4.

In general, China's investments in the equipment manufacturing industry, in terms of human, material, and financial resources, have been on the rise. Internal, external, and new product development funds have increased by 67.75%, 81.51%, and 51.89%, respectively. Investments in R&D personnel, in terms of total manpower (person) and full-time equivalent (person/year), have also increased by 42.40% and 35.83%, respectively, while the expenditure for instruments and equipment increased by 91.28%. In terms of sub-industries, the research and development expenditure and R&D personnel funds of the metal products industry posted the highest growth rates, reaching more than 100%.

As shown in Table 5, in terms of the number of effective invention patents, sales revenue of new products, and industrial sales output value, the growth rates of the metal products industry have been significantly higher compared to the other six industries, while the growth rates for the instrument manufacturing industry have been relatively low. The results from these two sub-industries are basically consistent with the uptrends of innovation inputs shown in Table 4. This suggests that, to some extent, the input and output of science and technology exhibit some degree of consistency. In order to more objectively measure the impact of science and technology input on innovation output, additional quantitative analyses were conducted.

Table 2 Total profit of China's equipment manufacturing industry for 2011–2015 (Unit: CNY 100 million)

Industry	2011	2012	2013	2014	2015	Rate of change
1	1545.71	2096.40	2160.81	2239.34	2392.88	54.81%
2	3054.92	3071.03	3149.34	3142.93	3178.66	4.05%
3	2154.43	2333.98	2261.53	2186.65	2280.04	5.83%
4	5478.38	6158.60	7237.69	7349.93	8029.47	46.57%
5	3310.13	3822.89	4162.98	4524.31	5150.27	55.59%
6	2827.42	3826.33	4282.57	4563.74	5070.17	79.32%
7	612.83	663.37	720.76	743.75	820.70	33.92%
Total of equipment manufacturing industry	18,983.82	21,972.60	23,975.68	24,750.65	26,922.19	41.82%
National industry	61,396.33	68,378.91	68,154.89	66,187.07	71,921.43	17.14%
Proportion of equipment manufacturing industry in national industry	30.92%	32.13%	35.18%	37.39%	37.43%	21.05%

Table 3 Pollution emission intensity of China's equipment manufacturing industry (In 2011 and 2015)

Industry	Wastewater discharge intensity (10,000 tons/CNY 100 million)			Exhaust emission intensity (100 million cubic meters/CNY 100 million)			Emission intensity of solid waste (10,000 tons/CNY 100 million)		
	2011	2015	Rate of change	2011	2015	Rate of change	2011	2015	Rate of change
1	1.3072	0.8907	−31.86%	0.3877	0.1711	−55.87%	0.0206	0.0193	−6.62%
2	0.2994	0.2158	−27.93%	0.0408	0.0402	−1.55%	0.0053	0.0032	−40.04%
3	0.2546	0.2009	−21.06%	0.1211	0.0293	−75.77%	0.0060	0.0038	−35.64%
4	0.4561	0.3277	−28.16%	0.0955	0.0805	−15.75%	0.0092	0.0065	−29.98%
5	0.1921	0.1605	−16.43%	0.0304	0.0443	45.92%	0.0013	0.0012	−13.24%
6	0.7186	0.6438	−10.41%	0.0983	0.0897	−8.81%	0.0015	0.0017	10.39%
7	0.3012	0.2843	−5.62%	0.0136	0.0302	122.39%	0.0006	0.0009	43.70%
Total of equipment manufacturing industry	3.5291	2.7237	−22.82%	0.7874	0.4852	−38.37%	0.0446	0.0365	−18.21%

Evaluation of green economic development efficiency of the equipment manufacturing industry in China

This work first constructs the input-output evaluation index system and its corresponding time series of green development efficiency of the equipment manufacturing industry based on the statistical data of China Environmental Statistics Yearbook, China Industrial Statistics Yearbook, and China Science and Technology Statistics Yearbook. Then, the super-efficiency slacks based measure (SBM) model of unexpected output and the Malmquist index method is used based on DEA to analyze the green development efficiency of the equipment manufacturing industry. The super-efficiency DEA value of the industry can be calculated through static analysis. If the super efficiency DEA value of an industry is less than 1, its technical efficiency, scale efficiency, output deficiency, and redundancy value will be

Table 4 Technological innovation input of China's equipment manufacturing industry (In 2011 and 2015)

Industry	Internal expenditure for R&D (Unit: CNY 10,000)			External expenditure for R&D (Unit: CNY 10,000)			New product development funds (Unit: CNY 10,000)		
	2011	2015	Rate of change	2011	2015	Rate of change	2011	2015	Rate of change
1	1,112,914.1	2,826,592.8	153.98%	27,155.5	66,759.8	145.84%	1,275,446.9	2,808,475.6	120.20%
2	4,066,679.2	6,326,467.1	55.57%	190,051.1	254,037.8	33.67%	5,003,972.1	6,690,067.2	33.70%
3	3,656,607.7	5,671,357.4	55.10%	91,323.7	108,243.7	18.53%	4,580,085.7	6,108,741.8	33.38%
4	7,852,545.9	13,400,540.4	70.65%	831,412.1	1,502,224.8	80.68%	9,734,549.9	15,210,011.9	56.25%
5	6,240,087.6	10,127,296.8	62.29%	265,365.7	333,895.7	25.82%	7,683,598.7	11,290,147.1	46.94%
6	9,410,520.4	16,116,757.2	71.26%	351,424.9	932,935	165.47%	12,357,995.5	19,822,682.9	60.40%
7	1,208,652.9	1,809,272	49.69%	58,671.5	97,042	65.40%	1,483,066.3	2,042,431.4	37.72%
Total	33,548,007.8	56,278,283.7	67.75%	1,815,404.5	3,295,138.8	81.51%	42,118,715.1	63,972,557.9	51.89%
Industry	R&D personnel (person)			R&D personnel, full-time equivalent (person/year)			Expenditure for instruments and equipment (CNY 10,000)		
	2011	2015	Rate of change	2011	2015	Rate of change	2011	2015	Rate of change
1	57,959	122,646	111.61%	40,167.3	88,580	120.53%	1,892,409.6	2,018,064.7	6.64%
2	206,404	284,483	37.83%	154,694.2	205,657	32.94%	2,283,519.3	4,463,628.4	95.47%
3	188,022	242,589	29.02%	146,529.3	170,104	16.09%	1,620,236.7	3,003,747.5	85.39%
4	286,920	434,288	51.36%	220,087.3	328,160	49.10%	4,176,811.7	7,446,635.6	78.29%
5	265,703	380,990	43.39%	205,275.2	270,363	31.71%	3,553,947.3	6,885,227.5	93.73%
6	376,172	518,675	37.88%	318,017.5	426,583	34.14%	3,396,054.9	8,435,839.7	148.40%
7	75,784	91,038	20.13%	61,605.2	67,662	9.83%	441,251.3	960,425.8	117.66%
Total	1,456,964	2,074,709	42.40%	1,146,376	1,557,109	35.83%	17,364,230.8	33,213,569.2	91.28%

Table 5 Technological innovation output of China’s equipment manufacturing industry

Industry	Number of invention patents (number)			New product sales revenue (CNY 1000)			Industrial sales value (Billion Chinese Yuan)		
	2011	2015	Rate of change	2011	2015	Rate of change	2011	2015	Rate of change
1	4780	15,667	227.76%	15,547,665.8	35,548,896.4	128.64%	22,882.48	37,671.69	64.63%
2	13,464	40,413	200.16%	59,293,577.5	80,435,662.1	35.66%	39,992.18	47,172.7	17.95%
3	16,358	49,732	204.02%	44,792,465.5	60,276,516.6	34.57%	25,354.42	36,185.03	42.72%
4	12,071	41,155	240.94%	200,879,220.8	255,612,736.4	27.25%	62,256.41	90,161.26	44.82%
5	24,052	63,837	165.41%	109,980,157	165,025,929	50.05%	50,141.59	69,558.22	38.72%
6	62,159	170,387	174.11%	182,267,800.5	306,577,277.7	68.20%	62,567.28	91,378.86	46.05%
7	6759	16,723	147.42%	14,584,253.3	18,734,367.5	28.46%	7444.16	8749.31	17.53%

further calculated to conduct an in-depth analysis of the evaluation results. The TEC, TC, MI, PTC, and SE values of China’s equipment manufacturing industry and sub-industries can be calculated by dynamic analysis. The evaluation results are analyzed in depth. The specific process is shown in Fig.1.

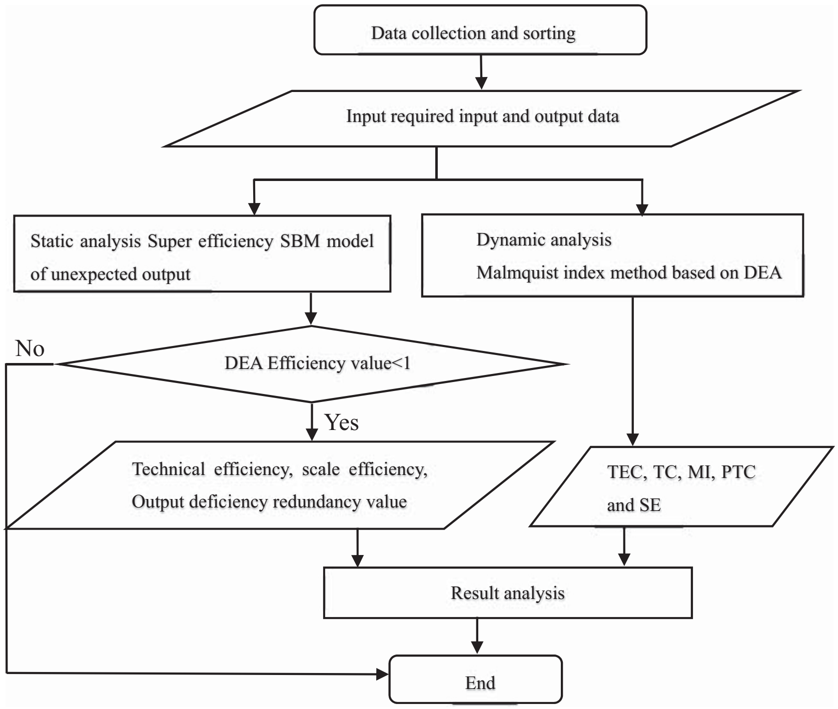
Research methods

Super efficiency SBM model of unexpected output

Since classic Date Envelopment Analysis (DEA) is unable to deal with the unexpected output directly, the super-efficiency SBM model of unexpected output can be used instead. The super-efficiency SBM model initially determines the effective decision-making units using the SBM model and then employs the super efficiency SBM for sorting. The model considers N decision-making units, with each unit consisting of M no. of inputs, S no. of expected outputs, and Q no. of unexpected outputs. The model is as follows:

$$\begin{cases} \min\phi = \dfrac{1+\dfrac{1}{M}\sum\limits_{m=1}^{M}\dfrac{X'_m}{X_{mk}}}{1-\dfrac{1}{(N+Q)}\times\left(\sum\limits_{s=1}^{S}\dfrac{Y'_s}{Y_{sk}}+\sum\limits_{q=1}^{Q}\dfrac{Z'_q}{Z_{qk}}\right)} \\ \sum\limits_{i=1,\neq n}^{N} X_{mi}\mu_i - X'_m \leq X_{mk} \quad m = 1,2,\cdots,M \\ \sum\limits_{i=1,\neq n}^{N} Y_{si}\mu_i + Y'_s \geq Y_{sk} \quad s = 1,2,\cdots,S \\ \sum\limits_{i=1,\neq n}^{N} Z_{qi}\mu_i - Z'_q \leq Z_{qk} \quad q = 1,2,\cdots,Q \\ \mu_i \geq 0 \quad i = 1,2,\cdots,N \\ X'_m \geq 0 \quad Y'_s \geq 0 \quad Z'_q \geq 0 \end{cases} \tag{2}$$

Fig. 1 Process of the evaluation



where ϕ is the objective function; X, Y, and Z are the production input factors, expected output factors, and unexpected output factors, respectively; the input, expected output, and unexpected output of the k^{th} decision are recorded as X_{mk}, Y_{sk}, and X'_{m}, respectively; Z_{qk}, Y'_{s}, and Z'_{q}, are the slack adjustment values of the three elements; and μ_i are the weights.

Malmquist index method based on DEA

In 1953, Malmquist first proposed the Malmquist index. Caves et al. (1982) then used it to measure productivity and proposed the Malmquist productivity index. Fare et al. (1994) further developed it into a production technology index using distance function to describe multiple input variables and multiple output variables (Malmquist 1953). The DEA method and the Malmquist index method can be combined in order to reflect the change of productivity between two periods. Such an approach would provide the relative efficiency of the decision-making unit $t+1$ period relative to the t period, which can be used to determine whether the efficiency improved during the t period. Taking the technology in period t as reference, the Malmquist index, based on the output angle, can be expressed as follows:

$$M_0^t\left(x^{t+1},\quad y^{t+1},\quad x^t,\quad y^t\right) = \frac{d_0^t\left(x^{t+1},\quad y^{t+1}\right)}{d_0^t\left(x^t,\quad y^t\right)} \tag{3}$$

In the same manner, the Malmquist index, based on output with reference to the technology of period $t+1$, can be expressed as follows:

$$M_0^{t+1}\left(x^{t+1},\quad y^{t+1},\quad x^t,\quad y^t\right) = \frac{d_0^{t+1}\left(x^{t+1},\quad y_{t+1}\right)}{d_0^{t+1}\left(x^t,\quad y^t\right)} \tag{4}$$

In order to avoid differences caused by the randomness of the period selection, Caves et al. (1982) used the geometric mean value of the two as the Malmquist index to measure the change of productivity from t to $t+1$:

$$M_0^{t\quad t+1}\left(x^{t+1},\quad y^{t+1},\quad x^t,\quad y_t\right) = \tag{5}$$

$$\left[\frac{d_0^t\left(x^{t+1},\quad y^{t+1}\right)}{d_0^t\left(x^t,\quad y^t\right)} \times \frac{d_0^{t+1}\left(x^{t+1},\quad y^{t+1}\right)}{d_0^{t+1}\left(x^t,\quad y^t\right)}\right]^{\frac{1}{2}}$$

where (x^{t+1}, y^{t+1}) and (x^t, y^t) are the input and output vectors of periods $t+1$ and t, respectively; and, d_0^t and d_0^{t+1} are the distance functions of periods t and $t+1$, respectively, with the technology of the t period as reference.

The Malmquist index can be divided into technical efficiency change (TEC) and technical change (TC). The decomposition process is expressed as:

$$M_c^{t\quad t+1}\left(x^{t+1},\quad y^{t+1},\quad x^t,\quad y^t\right) = \tag{6}$$

$$\frac{d_c^{t+1}(x_{t+1},\quad y_{t+1})}{d_c^t\left(x^t,\quad y^t\right)}\left[\frac{d_c^t(x_{t+1},\quad y_{t+1})}{d_c^{t+1}\left(x_{t+1}\quad y_{t+1}\middle|\quad C\right)} \times \frac{d_c^t\left(x_t,\quad y^t\right)}{d_c^{t+1}\left(x^t,\quad y_t\right)}\right]^{\frac{1}{2}}$$

The TEC can be further divided into pure technical efficiency (PTE) and scale efficiency (SE). The equation can then be converted into:

$$\begin{aligned} M_{\nu\quad c}^{t\quad t+1} &= \frac{d_\nu^{t+1}(x_{t+1},\quad y_{t+1})}{d_\nu^t\left(x^t,\quad y^t\right)} \times \left[\frac{d_\nu^t(x_t,\quad y_t)/d_c^t\left(x^t,\quad y^t\right)}{d_\nu^{t+1}(x_{t+1},\quad y_{t+1})/d_c^{t+1}\left(x^{t+1},\quad y^{t+1}\right)}\right] \\ &\times \left[\frac{d_c^t(x_{t+1},\quad y_{t+1})}{d_c^{t+1}\left(x_{t+1}\quad y_{t+1}\middle|\quad C\right)} \times \frac{d_c^t\left(x_t,\quad y^t\right)}{d_c^{t+1}\left(x^t,\quad y_t\right)}\right]^{\frac{1}{2}} \\ &= PTE \times SE \times TC = TEC \times TC \end{aligned} \tag{7}$$

TEC indicates the degree of catching up from the decision-making unit to the production frontier from t to $t+1$ and refers to the distance between the actual output and the production frontier. TC represents the change in the production frontier of the decision-making unit for two adjacent periods. PTE refers to the technical efficiency wherein the return on the scale remains unchanged. The PTE is the degree of catching up of each decision-making unit to the frontier under the assumption that the optimal production scale stays constant. SE indicates whether the decision-making unit tends towards the optimal production scale.

Index selection

The DEA model has been widely used in various research applications but contains a number of intrinsic methodological limitations. As an alternative, the non-radial and non-angle SBM model has been proposed to overcome some of the inherent constraints of the DEA model. In addition, some researchers have established a green innovation efficiency model, including R&D input, energy input, innovation output, and environmental output based on the innovation efficiency model. Considering the completeness and integrity of available data, the input and output indexes selected in this study are as follows:

(1) Input indexes. The internal and external expenditures of R&D funds, number of R&D personnel, and equivalent full-time R&D personnel were used as proxy indicators (capital and manpower) to measure the investment of scientific and technological innovation in the equipment manufacturing industry, and the expenditure for instruments and equipment was used as the material input.

(2) Output indicators. The output indicators mainly consist of expected output and unexpected output. The expected output refers to the positive output of scientific and technological innovation activities. The number of effective invention patents, new product sales revenue, and industrial sales output were used to measure expected output in this study. Non-expected output refers to the negative output of environmental regulation. Here, emission intensities of wastewater, waste gas, and solid waste were used as indicators for the non-expected output.

Results and discussion

Static analysis of green economic development efficiency

The super-efficiency SBM model was used to evaluate the green economic development efficiency of China's equipment manufacturing industry for 2010–2015 in the seven sub-industries. As shown by the results (Table 6), the efficiency value of the instrument manufacturing industry is more than one in 2014, and less than one for the remaining years. This indicates that efficiency in the green economic development for the instrument manufacturing industry has been relatively low, and further optimization and improvements are needed. The super-efficiency DEA of the remaining six industries is greater than one for each year. The efficiency value of the electrical machinery and equipment manufacturing industry was found the highest, indicating that the industry has become more mature compared to the other sub-industries, and the overall development is stable.

For the instrument manufacturing industry with super efficiency DEA value less than one, further assessment was conducted to determine the PTE, SE, scale income, and potential value of output factors. The results are presented in Table 7.

Table 6 Super efficiency DEA of the green economic development in China's equipment manufacturing industry

Industry	2011	2012	2013	2014	2015
1	1.158	1.203	1.127	1.157	1.107
2	1.032	1.011	1.017	1.019	1.016
3	1.057	1.034	1.092	1.119	1.166
4	1.094	1.065	1.039	1.055	1.052
5	1.322	1.361	1.336	1.322	1.284
6	1.148	1.224	1.148	1.27	1.164
7	0.580	0.466	0.487	1.003	0.539
Mean value	1.147	1.038	0.996	1.010	1.115

The scale efficiency less than one is the primary reason for the limited benefits gained from green economic development. In particular, strategies to improve sales revenue from new products in the instrument manufacturing industry have to be planned and implemented. This may involve further strengthening of investments in scientific and technological research and development. As for the unexpected outputs, wastewater discharge was shown to be the most prevalent environmental problem, which indicates that further policy refinement and administrative measures have to be introduced in order to focus on reducing wastewater pollution.

Dynamic analysis of green economic development efficiency

The Malmquist index method of the SBM model was used to analyze the green economic development efficiency. A comparative assessment was conducted with regard to the changes in the dynamic evolution of green growth efficiency for the entire equipment manufacturing industry and its seven sub-industries. The results of the assessment are summarized in Table 8.

Figure 2 shows the trend of TEC, TC, and MI. The results show TEC and MI have similar trends, which show a low-to-high-to-low movement. Meanwhile, TC is shown to have an upward trend at the later stage, which suggests a substantial pulling effect from improvements of MI.

Table 8 shows the Malmquist indexes exhibits a low-high-low trend, with an average value of 0.9817. Being less than one, this suggests that there is still plenty of room to improve green growth efficiency in the equipment manufacturing industry. Further decomposition of the Malmquist index shows that the technical progress index has a value greater than one, while but its technical efficiency is less than one. Further analysis shows that both pure technical and scale efficiency indexes are less than one. This suggests that the pure technical efficiency of investment in the equipment manufacturing industry has been in decline and that the innovation power is insufficient. The input-output efficiency needs to be further optimized, which would necessitate further increases in science and technology inputs and significant reduction of pollutants. The Malmquist indexes for 2010–2012 were less than one and were above one for 2012–2015. This indicates that green economic development efficiency has since improved and has fairly stabilized.

Horizontal comparison of the equipment manufacturing sub-industries (Table 9) shows that the Malmquist indexes of the special equipment manufacturing (3), electrical machinery and equipment manufacturing (5), and the computer, communication, and other electronic equipment

Table 7 PTE, SE, scale income, and potential value of output factors of instrument manufacturing industry

Year	PTE	SE	Scale income	△ Expected output 1	△ Expected output 2	△ Expected output 3	△ Unexpected output 1	△ Unexpected output 2	△ Unexpected output 3
2011	8.404	0.069	irs	0.000	6,209,922.375	0.000	− 0.225	− 0.003	0.000
2012	4.720	0.099	irs	0.000	4,510,592.578	0.000	− 0.306	− 0.037	− 0.001
2013	7.774	0.063	irs	0.000	8,074,188.737	0.000	− 0.147	− 0.009	− 0.001
2015	5.764	0.094	irs	0.000	11,355,321.355	219.266	− 0.221	− 0.021	0.000

△Expected output 1: effective invention patent; △Expected output 2: new product sales revenue; △Expected output 3: industrial sales value; △Unexpected output 1: wastewater discharge intensity; △Unexpected output 2: waste gas discharge intensity; △Unexpected output 3: solid waste discharge intensity

manufacturing (6) industries are greater than one. This suggests that these sub-industries have shown exhibited development trends. According to the decomposition index, the improvements in their green growth efficiency have been driven mainly by the technology progress index. The average annual green growth efficiency values of the metal products (1), general equipment manufacturing (2), transportation equipment manufacturing (4), and instrument manufacturing (7) industry are less than one, with the instrument manufacturing declining by as much as 12.13%. The pure technical efficiency of the instrument manufacturing industry is 1.4195, while the scale efficiency is only 0.6055. This deficit in scale efficiency significantly restricts development, which means that necessary adjustments to the scale of investments would be necessary to further promote growth.

Flexible government regulation and technological innovation are conducive to the development of green economy

Under the background of resource and environment constraints, economic development must be combined with ecological development. Equipment manufacturing industry is the foundation of a country's industry, but at the same time, it faces the problem of pollution discharge. Therefore, it is imperative to coordinate the relationship between the development of equipment manufacturing industry and environmental protection. Scientific and technological innovation is an important factor to coordinate economic development and environmental protection, and the UNEP report also emphasizes the important role of science and technology in improving environmental conditions. This study shows that technological innovation can make enterprises solve environmental problems with the minimum cost, and can improve the profit margin of enterprises through technological innovation behavior. The technology progress index is the main driving force to improve the efficiency of green economic development in China's equipment manufacturing industry. In the later stage, it is necessary to further optimize the scale efficiency and in view of the heterogeneity of different industries. The government departments should formulate different environmental policies and increase the support for scientific research funds for different industries.

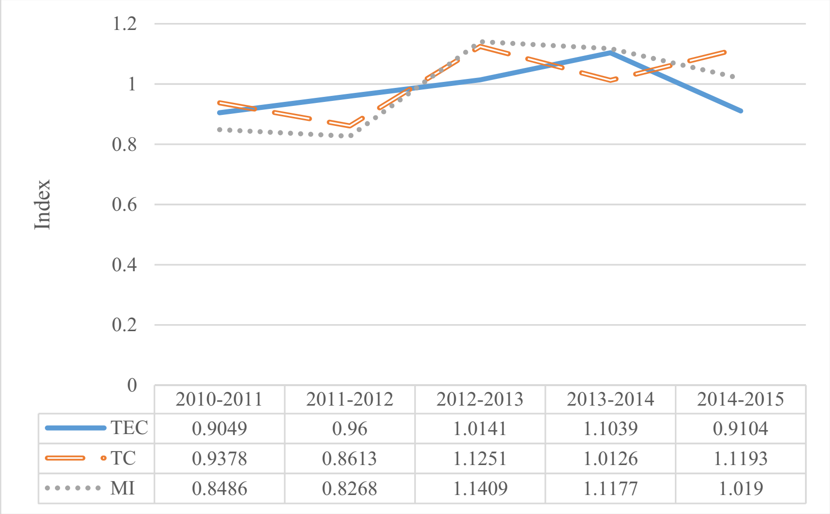
Table 8 Malmquist index of China's equipment manufacturing industry (2011–2015)

Year	TEC	TC	MI	PTE	SE
2010–2011	0.9049	0.9378	0.8486	0.9678	0.9351
2011–2012	0.9600	0.8613	0.8268	0.9621	0.9979
2012–2013	1.0141	1.1251	1.1409	0.9770	1.0379
2013–2014	1.1039	1.0126	1.1177	0.9932	1.1114
2014–2015	0.9104	1.1193	1.0190	0.9989	0.9114
Mean value	0.9759	1.0059	0.9817	0.9797	0.9962

MI Malmquist index

Conclusion

Overall, the output value and profits from industrial sales of the entire equipment manufacturing industry are increasing, and the economic benefits are rising steadily. The economic growth of the manufacturing industry is higher than the growth of the entire industry, but the rate has been slowing down. The environmental regulation effect of the whole industry has been evident. The control effect of wastewater discharge intensity is the most pronounced, while the wastewater pollution discharge intensity among the seven sub-industries has been on a significant decline. Investments in human, material, and financial resources in research and development has been increasing, but there are significant differences among the different sub-industries. The transportation equipment manufacturing and the computer, communication, and other electronic equipment



	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015
TEC	0.9049	0.96	1.0141	1.1039	0.9104
TC	0.9378	0.8613	1.1251	1.0126	1.1193
MI	0.8486	0.8268	1.1409	1.1177	1.019

Fig. 2 Trend chart of three indexes

manufacturing have the best economic benefits. At the same time, the technological innovation inputs of these two sub-industries are top-ranked, but the decline in their pollution emission intensity has not been among the best. The metal products industry does not rank high in terms of economic benefits, but it has the highest rank in terms of R&D investments towards technological innovation and pollution emission intensity control. This suggests that in the short term, environmental regulations would restrain economic growth, but in the long run, they can improve profit by encouraging enterprises to improve their production levels. Scientific and technological innovation is an essential factor influencing industrial economic development and environmental protection. Significantly reducing emissions is crucial in improving environmental quality. But since pollution has often accompanied traditional industrial operations and development, greater scientific and technological innovation promoting environmentalism has to supplement adherence to environmental regulations.

In this study, the super efficiency SBM model and DEA Malmquist index model have been used to evaluate the green economic development efficiency of China's equipment manufacturing industry from static and dynamic aspects. At present, environmental regulations on China's equipment manufacturing industry has a restraining effect on technological innovation, significantly constraining short-term economic growth in the industry. Moreover, the results found that the enterprise-scale and R&D investments have a substantial restraining effect on the equipment manufacturing industry. Technological innovation plays a significant role in promoting, optimizing the management mode and scale management, and improving scale efficiency. Medium and long-term strategies and policies should include ways to improve the environmental regulation intensity, increase public and private funding intended for research and development, and address the differences and particular needs of the different sub-industries.

Table 9 Malmquist index of China's equipment manufacturing industry by industry (2011–2015)

Industry	TEC	TC	MI	PTE	SE
1	0.9945	0.9865	0.9811	1.0061	0.9884
2	0.9946	1.0010	0.9956	0.9821	1.0127
3	1.0049	1.0082	1.0131	1.0135	0.9915
4	0.9969	0.9980	0.9950	0.9900	1.0070
5	0.9876	1.0218	1.0091	0.6136	1.6095
6	1.0029	1.0037	1.0066	1.0030	0.9999
7	0.8593	1.0225	0.8787	1.4195	0.6053

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References

Arimura TH, Sugino M (2007) Does stringent environmental regulation stimulate environment-related technological innovation? Sophia Econ Rev 52:1–14

Berman E, Bui LTM (2001) Environmental regulation and productivity: evidence from oil refineries. Rev Econ Stat 83:498–510

Bos JWB, Economidou C, Sanders MWJL (2013) Innovation over the industry life-cycle: evidence from EU manufacturing. J Econ Behav Organ 86:78–91

Brännlund R, Färe R, Grosskopf S (1995) Environmental regulation and profitability: an application to Swedish pulp and paper mills. Environ Resour Econ 6:23–36

Caves DW, Christensen LR, Diewert WE (1982) The economic theory of index numbers and the measurement of input and output,and productivity. Econometrica 50:1938–1414

Fare R, Grosskopf S, Norris M, Zhang ZY (1994) Productivity growth, technical progress and efficiency changes in industrialized countries. Am Econ Rev 84:66–83

Fortin HWM (2005) Spatial analysis of landscape:concepts and statistics. Ecology 86(8):1975–1987

Freeman AM, Haveman RH, Kneese AV (1972) Economics of environmental policy. Nature 376(6539):444–447

Gray WB, Shadbegian RJ (2003) Plant vintage, technology,and productivity, and environmental regulation. J Environ Econ Manag 46: 384–402

He BJ, Zhao DX, Zhu J, Darko A, Gou ZH (2018) Promoting and implementing urban sustainability in China: an integration of sustainable initiatives at different urban scales. Habitat Int 82:83–93

Jaffe AB, Palmer K (1997) Environmental regulation and innovation: a panel data study. Rev Econ Stat 79:610–619

Jerath M, Bhat M, Rivera-Monroy VH, Castañeda-Moya E, Simard M, Twilley RR (2016) The role of economic, policy, and ecological factors in estimating the value of carbon stocks in Everglades mangrove forests, South Florida, USA. Environ Sci Pol 66:160–169

Kang YQ, Xie BC, Wang J, Wang YN (2018) Environmental assessment and investment strategy for China's manufacturing industry: a non-radial DEA based analysis. J Clean Prod 175:501–511

Kuosmanen T, Bijsterbosch N, Dellink R (2009) Environmental cost-benefit analysis of alternative timing strategies in greenhouse gas abatement: a data envelopment analysis approach. Ecol Econ 68: 1633–1642

Lanoie P, Patry M, Lajeunesse R (2008) Environmental regulation and productivity: testing the Porter hypothesis. J Prod Anal 30:121–128

Magat WA (1978) Pollution control and technological advance: a dynamics model of the firm. J Environ Econ Manag 5:1–25

Malmquist S (1953) Index numbers and indifference surfaces. Trab Estad 4(2):209–242

Matthews RCO (1981) Accounting for slower economic growth: the United States in the 1970s. Econ J 91:1044–1046. https://doi.org/10.2307/2232516

National Bureau of Statistics of China, Ministry of Ecology and Environment (2018) China Statistical Yearbook on Environment. China Statistical Press, Beijing

Porter ME, Claas VDL (1995) Toward a new conception of the environment-competitiveness relationship. J Econ Perspect 9:97–118

Qin G, Zhang P, Hou X, Wu S, Wang Y (2020) Risk assessment for oil leakage under the common threat of multiple natural hazards. Environ Sci Pollut Res 1–14. https://doi.org/10.1007/s11356-020-08184-7

Ramnathan R, Black A, Nath P, Muyldermans L (2010) Impact of environmental regulations on innovation and performance in the UK industrial sector. Manag Decis 48:1493–1513

Shen N, Liao H, Deng R, Wang Q (2019) Different types of environmental regulations and the heterogeneous influence on the environmental total factor productivity: empirical analysis of China's industry. J Clean Prod 211:171–184

Stephens JK, Denison EF (1981) Accounting for slower economic growth: the United States in the 1970s. South Econ J 47:1191

Telle K, Larsson J (2007) Do environmental regulations hamper prodictivity growth? How accounting for improvenments of plants environmental performance can change the conclusion. Ecol Econ 61:438–445

Testa F, Iraldo F, Frey M (2011) The effect of environmental regulation on firms' competitive performance: the case of the building & construction sector in some EU regions. J Environ Manage 92:2136–2144

Wang H, Xu J, Wang D, Zhang T, Liu Y (2015) Cleaner production based on sustainable development in Chinese power plants. Environ Eng Sci 32:6

Wang Y, Yan W, Ma D, Zhang C (2018) Carbon emissions and optimal scale of China's manufacturing agglomeration under heterogeneous environmental regulation. J Clean Prod 176:140–150

Wang H, Xu J, Sheng L (2020) Purification mechanism of sewage from constructed wetlands with zeolite substrates: a review. J Clean Prod 258:120760

Yang CH, Tseng YH, Chiang CP (2012) Environmental regulations, induced R&D, and productivity; evidence from Taiwan's manufacturing industries. Resour Energy Econ 34:514–532. https://doi.org/10.1016/j.reseneeco.2012.05.001

Yuan B, Xiang Q (2018) Environmental regulation, industrial innovation and green development of Chinese manufacturing: based on an extended CDM model. J Clean Prod 176:895–908

Yuan B, Ren S, Chen X (2017) Can environmental regulation promote the coordinated development of economy and environment in China's manufacturing industry? A panel data analysis of 28 sub-sectors. J Clean Prod 149:11–24

Zhou M (2017) Valuing environmental amenities through inverse optimization: theory and case study. J Environ Econ Manag 83:217–230