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Study on the Environmental Efficiency of the Chinese Cement Industry Based on the Undesirable Output DEA Model

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Abstract: In recent decades, China's cement production has been the highest in the world, but the extensive development model, which has been formed for a long time, has brought serious damage to the natural environment. In order to promote the transformation of the production mode of China's cement industry, this paper adopts the nonparametric frontier method to analyze the environmental efficiency of China's cement manufacturing industry using the input–output and pollutant emission data of China's cement manufacturing industry from 2004 to 2016. The results show that the overall environmental efficiency of China's cement industry is low, and there is still much room for improvement. Moreover, there are serious imbalances from very low to very high between different regions. Further investigation found that during the study period, strict environmental supervision brought an average compliance cost of CNY 23.41 billion to China's cement manufacturing industry, but the overall environmental efficiency increased by 23.9 percentage points. Based on these findings, we believe that the focus of environmental supervision of China's cement manufacturing industry at this stage is to reduce pollution emissions, and force cement enterprises to carry out technological innovation through mandatory emission reduction measures. When formulating policies, the Chinese government needs to explore the best way for environmental supervision between minimizing compliance costs and maximizing efficiency, so as to promote the sustainable development of China's cement manufacturing industry.

Keywords: environmental efficiency; efficiency loss; DDF; Chinese cement industry

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Citation: Tu, H.; Dai, W.; Xiao, X. Study on the Environmental Efficiency of the Chinese Cement Industry Based on the Undesirable Output DEA Model. *Energies* **2022**, *15*, 3396. https://doi.org/10.3390/en15093396

Academic Editor: Joaquim Rovira

Received: 21 March 2022
Accepted: 26 April 2022
Published: 6 May 2022

1. Introduction

The cement industry is closely related to the development of the national economy, production and construction, and people's life, and its output value accounts for 40% of the building materials industry. China's cement industry has a history of nearly one hundred years, and especially in the past 10 years, with a rapid development momentum and the output ranking of first in the world for many years. However, as a traditional industrial sector, the cement manufacturing industry has the typical characteristics of high energy consumption, high emissions, and resource dependence, which inevitably brings a series of environmental pollution problems. According to incomplete statistics, the dust (smoke) emitted by China's cement manufacturing industry accounts for 39% of the total industrial dust emissions in China, and the dust (smoke) emitted per unit land area is 8.45 times the world average, ranking first in industrial dust emissions [1]. In terms of air pollution control, the cement manufacturing industry has become the third major monitoring object next to thermal power and transportation. In addition, PM2.5 accounts for more than 80% of the dust emissions of China's cement manufacturing industry, and the emission of NO_x accounts for about 10–12% of the total amount of the country, which has become an important driver of hazy weather. In reality, the pollution emissions of

China's cement manufacturing industry are seriously exceeding the standard. It is urgent for the state to formulate relevant regulatory measures to guide the healthy and sustainable development of the cement industry. Based on this, this paper selects the heavily polluted cement manufacturing industry as the research object, and empirically analyzes the impact of national environmental regulation policies on the cement manufacturing industry, so as to provide policy support for promoting the sustainable development of the cement manufacturing industry.

2. Literature Review

Environmental efficiency is an important indicator to describe the coordinated development of energy, environment, and economy. It has always been a hot topic in academia and for policymakers. Many scholars use different methods to study energy and environmental efficiency from different perspectives. Their research methods mainly include the parametric method and the nonparametric method, but the nonparametric method is more common. For example, Rehman's research team has used the parameter analysis method to study the complex relationship between regional energy, economy, and environment, and has achieved fruitful research results [2–7]. However, because the nonparametric DEA method does not need to know the specific form of the production frontier and has great flexibility, more and more researchers apply it to environmental efficiency evaluation. Different from the traditional concept of technical efficiency, environmental efficiency is an efficiency evaluation system based on environmental technology. It is a technical efficiency considering environmental pollution factors. In the process of industrial production, when the input of resource factors is certain, its output shows two distinct forms: one is normal output, that is, industrial economic growth and social welfare increase; the other is abnormal output, which shows various pollution emissions in the process of industrial production, and this abnormal output is nonremovable. Because two different forms of output show the reverse change relationship of one increase and one decrease, the evaluation of environmental efficiency becomes extremely complex. The simple ratio analysis method and the traditional DEA model are no longer applicable. It was not until Chambers and Chung et al. (1996) proposed the directional distance function based on the traditional Shepard output distance function that the problem of environmental efficiency evaluation under environmental governance was reasonably solved [8]. Since then, this nonparametric method has been widely used by scholars such as Chou (2013), Li (2013), and Song (2015) to study the coordinated development of the energy economy environment (3E) in China [9–11].

As a traditional industrial sector, the cement manufacturing industry has obvious production process characteristics of high energy consumption, high emissions, and resource dependence, which will inevitably bring a series of environmental pollution problems. Unfortunately, the existing research literature rarely involves the environmental efficiency of the cement industry. For example, Oggioni et al. [12] analyzed the eco-efficiency of 21 prototypes of the cement industry using a DDF approach. Riccardi et al. [13] assessed the efficiency of the high energetic and CO_2 emission-intensive cement production processes in 21 countries using the distance function and the directional distance function. Long et al. [14] investigated the total factor productivity eco-efficiency and the determinants of Malmquist in China's cement manufacturers. Zhang et al. [15] analyzed the environmental efficiency of China's listed cement companies using a non-radical DEA model with a slacks-based measure. The above research focuses more on the macro level to explore the 3E problem of the cement industry. The Chinese government has always adhered to the binding indicators of resource conservation and environmental protection for many years. What is the effect of government regulation policies? What impact does it have on the environmental performance of China's cement industry? What differences are there between different regions? Existing studies cannot answer these questions. Enterprise organizations are the subject of national environmental supervision and the executor of regulatory policies. Only by analyzing the environmental efficiency of the cement manufacturing industry from the industry and enterprise level can we accurately answer the above questions.

Based on this, this paper selects the pollution-intensive Chinese cement manufacturing industry as the research object. From the perspective of introducing environmental regulation, we use the DDF model to comprehensively analyze the efficiency loss, regulation cost, and regional differences caused by environmental regulation in China's cement industry from 2004 to 2016, so as to enrich the existing research literature.

3. Methods and Data

3.1. DDF Model

In this paper, 30 provinces of China's cement manufacturing industry (i = 1, 2, . . . , 30) were selected as the research object, and the research period was 13 years in total (t = 2004, 2005, . . . , 2016). Each production unit had three kinds of inputs (x_1, x_2, x_3), one kind of desirable output (y), and two kinds of undesirable output (b_1, b_2). Then, the environmental technology of the production unit i at time t can be simulated by the following production set [16]:

$$P(x^{i,t}) = \left\{ \left(y^{i,t}, b^{i,t}\right) : x^{i,t} \ can \ produce \left(y^{i,t}, b^{i,t}\right) \right\} \tag{1}$$

The possible frontiers of all environmental outputs are given by $P\left(x^{i,t}\right)$, that is, all sets of good and bad products that can be produced under a given input. Although environmental technology provides all possible frontiers of environmental output, it cannot reflect the public's demand for increasing output and reducing pollution under the condition of certain input. Based on the research needs, this paper introduces the directional distance function model under fixed input proposed by Chung and Färe et al. [17] as the basic model:

$$\vec{D}_0\left(x^{i,t}, y^{i,t}, b^{i,t}; g_y, -g_b\right) = \sup\left[\beta : \left(y^{i,t} + \beta g_y, b^{i,t} - \beta g_b\right) \in P\left(x^{i,t}\right)\right] \tag{2}$$

In the above formula, we select the direction vector $g = \left(g_y, -g_b\right)$ to indicate the increase or decrease of the desirable output (y) and the undesirable output (b) in the same proportion on the vector path determined by the direction vector g. β is the maximum possible number of y increasing and b decreasing. Therefore, β can be used to measure the nonefficiency of a production unit relative to the technological level of the frontier environment [18].

Assuming that the undesirable output is disposed of freely, energy and environment do not restrict the output, and the disposal of "bad" products becomes a free activity, so the manufacturer does not need to bear the extra cost to reduce the undesirable output. At this time, the optimal solution γ_s of the directional distance function of the production unit $k(x^{i,t}, y^{i,t}, b^{i,t})$ in the reference environment technology $P(x^{i,t})$ can be solved by the linear planning (3) of the free disposal of the directional distance function.

$$\begin{aligned}
& \vec{D}_0^S\left(x^{i,t}, y^{i,t}, b^{i,t}; g_y, -g_b\right) = \max_{\gamma \geq 0} \gamma \\
s.t. \quad & \textstyle\sum_i z^i y_m^{i,t} \geq (1+\gamma) y_m^{i,t} \qquad m = 1 \\
& \textstyle\sum_i z^i b_j^{i,t} \geq (1-\gamma) b_j^{i,t} \qquad j = 1,2 \\
& \textstyle\sum_i z^i x_n^{i,t} \leq x_n^{i,t} \qquad n = 1,2,3 \\
& \textstyle\sum_i z^i = 1 \ z^i \geq 0 \qquad i = 1,2,\ldots,30
\end{aligned} \tag{3}$$

However, in real production, it is impossible to reduce the undesirable output without cost. Removing the "bad" output will inevitably occupy a certain amount of production resources. Manufacturers will not voluntarily reduce "bad" output; the government must enforce the behavior of manufacturers through environmental regulation. Therefore, the undesirable output under the consideration of environmental factors is not free disposal.

At this time, the optimal solution β_W of the directional distance function can be solved by linear planning (4) of the weak disposal directional distance function.

$$\begin{array}{ll} & \vec{D}_0^W\left(x^{i,t}, y^{i,t}, b^{i,t}; g_y, -g_b\right) = \max_{\beta \geq 0} \beta \\ s.t. & \sum_i z^i y_m^{i,t} \geq (1+\beta) y_m^{i,t} \qquad m = 1 \\ & \sum_i z^i b_j^{i,t} \geq (1-\beta) b_j^{i,t} \qquad j = 1,2 \\ & \sum_i z^i x_n^{i,t} \leq x_n^{i,t} \qquad n = 1,2,3 \\ & \sum_i z^i = 1\ z^i \geq 0 \qquad i = 1,2,\ldots,30 \end{array} \quad (4)$$

Although the difference between planning (3) and (4) lies only in the symbolic difference in constraints, the economic meanings expressed are quite different. The equal sign constraint of undesirable output in planning (4) endows it with the technology assumption of weak disposal, that is, it needs to pay a price to reduce "bad" output, so the idea of environmental regulation is incorporated into the existing research framework.

3.2. Environmental Regulation Cost and Regulation Efficiency Loss

The characteristics of environmental technology stipulate that desirable output and undesirable output have joint weak disposability. If $(y, b) \in P(x)$, $0 \leq \theta \leq 1$, then $(\theta y, \theta b) \in P(x)$, reducing the undesirable output (b) will inevitably lead to a decrease in the desirable output (y). Therefore, by comparing the output under the assumption of free disposal and weak disposal, the difference between the two is the impact of environmental regulation on output, that is, the cost of environmental regulation (*ERC*) [19]:

$$ERC^{i,t} = \left[\vec{D}_0^S\left(x^{i,t}, y^{i,t}, b^{i,t}; g_y, -g_b\right) - \vec{D}_0^W\left(x^{i,t}, y^{i,t}, b^{i,t}; g_y, -g_b\right)\right] y_m^{i,t} \quad (5)$$

At this time, the difference between the distance function value γ_S and β_W under two different disposal assumptions is the potential efficiency loss caused by environmental regulation (*REL*) [20]:

$$REL^{i,t} = \left[\vec{D}_0^S\left(x^{i,t}, y^{i,t}, b^{i,t}; g_y, -g_b\right) - \vec{D}_0^W\left(x^{i,t}, y^{i,t}, b^{i,t}; g_y, -g_b\right)\right] = \gamma_S - \beta_W \geq 0 \quad (6)$$

3.3. Variables' Description and Data Source

Based on the principle of data accessibility and referring to previous studies [21–23], we selected fixed asset investment (x_1), number of employees (x_2) at the end of the year, and energy consumption (x_3) as factor input indicators, industrial added value (y) as desirable output indicators, and dust (smoke) emission (b_1) and SO_2 emission (b_2) as undesirable output indicators. Relevant input–output variables and description of the data source are shown in Table 1.

Using the statistical yearbook data released by relevant authorities in China, the descriptive statistics of each variable as shown in Table 2 were obtained by manual sorting. In terms of input factors, the average completed investment in fixed assets of the cement manufacturing industry above the designated size in the central region were CNY 3.26 billion, CNY 2.63 billion in the western region, and CNY 1.98 billion in the eastern region. The central and western regions were significantly higher than the national average. The average number of employees absorbed by the cement manufacturing industry in the central region reached 48,900, ranking first among the three regions. This shows that the central and western regions have become the key areas for the development of China's cement industry. The average of the total energy consumption of the cement manufacturing industry above the national scale is 4.2 million tons of standard coal, and the standard deviation reaches 341.04. The large standard deviation indicates that the total energy consumption varies among different regions, which is the result of the imbalance of production of local cement manufacturing enterprises. Among them, the energy consumption in the central and eastern regions is basically at the same level. Due to the influence of production scale, the energy consumption of the above two regions is much higher than that of the western region. Moreover, there are great differences among different provinces in the three regions. From the analysis of industrial output, the industrial added value created by cement manufacturing above the designated size in the central region ranks first among the three regions, and the emission of dust (smoke) is much higher than that in other regions. SO_2 emission has basically maintained a relatively stable state, with little difference among the three regions.

Table 1. Variables and description of data source.

Variables		Description of Data Source
Input	Fixed assets investment completed (x_1)	The statistical scope of fixed assets investment is construction projects with a total planned investment of more than CNY 500,000, and the basic data are from the China Cement Yearbook over the years.
	Employees (x_2)	The number of employees of all industrial caliber are selected, and the statistical scope is enterprises above a designated size. The basic data come from the statistical data of the cement manufacturing industry in the China Cement Yearbook, China Statistical Yearbook, and China Labor Statistical Yearbook.
	Energy consumption (x_3)	Equivalent to 10,000 tons of standard coal. The basic data come from the statistical data of the cement manufacturing industry in the China Cement Yearbook, China Statistical Yearbook, and China Energy Statistical Yearbook.
Desirable output	Industrial Value added (y)	According to statistics, the annual sales revenue of state-owned enterprises above CNY 5 million is the total sales revenue of state-owned enterprises. The basic data come from the China Cement Yearbook.
Undesirable output	Dust(smoke) emission (b_1)	Dust (smoke) and SO_2 are the main pollution sources of the cement manufacturing industry. The basic data come from the statistical data of the cement manufacturing industry in the China Cement Yearbook, China Statistical Yearbook, and China Environmental Yearbook.
	SO_2 emission (b_2)	

Table 2. Descriptive statistics of input and output of cement manufacturing enterprises above the designated size.

		Input			Desirable Output	Undesirable Output	
		x_1 (CNY 100 Million)	x_2 (10,000 People)	x_3 (0.01 Mtec)	y (CNY 100 Million)	b_1 (10,000 ton)	b_2 (10,000 ton)
Nation wide	Mean	25.59	4.28	420.29	43.57	17.93	3.48
	Std. Dev.	29.60	3.02	341.04	45.98	13.64	2.44
	Maximum	227.45	16.25	1692.27	210.58	78.49	11.78
	Minimum	0.00	0.23	17.17	0.83	0.02	0.02
	N	390	390	390	390	390	390
Eastern	Mean	19.78	4.68	481.05	52.58	13.93	3.51
	Std. Dev	24.98	4.11	422.58	55.12	12.24	2.76
	Maximum	138.86	16.25	1692.27	210.58	59.51	11.31
	Minimum	0.00	0.23	17.17	1.80	0.02	0.02
	N	143	143	143	143	143	143
Central	Mean	32.60	4.89	481.52	48.34	25.75	3.48
	Std. Dev.	29.12	1.97	291.24	42.02	15.37	1.98
	Maximum	117.29	11.87	1512.50	185.50	78.49	8.95
	Minimum	0.93	1.93	125.63	5.09	4.72	0.67
	N	104	104	104	104	104	104
Western	Mean	26.30	3.44	315.00	31.58	16.25	3.46
	Std. Dev	33.03	2.04	246.78	35.09	11.17	2.41
	Maximum	227.45	9.48	1259.48	180.89	54.71	11.78
	Minimum	0.37	0.58	28.00	0.83	0.79	0.13
	N	143	143	143	143	143	143

From the discussion above, it indicates that the central region has become the core region of China's cement manufacturing industry and also the hardest hit area of pollution, while the western region is the region with the fastest growth rate and has huge development space in the future. The eastern region pays more attention to the upgrading of the industrial structure, and the development of high-end cement products will become the focus of industrial development in the future.

4. Results and Discussion

4.1. Calculation Results and Analysis of Environmental Efficiency

According to planning (3) and (4), we used MATLAB 7.0 software to calculate the optimal solution of inefficiency under free disposal and weak disposal, and calculate the environmental efficiency under two different disposal assumptions. According to the annual calculation results in Table 3, environmental regulation not only promotes the improvement of environmental efficiency, but also brings a certain degree of potential efficiency loss and regulation cost to the cement manufacturing industry. (1) Under the assumption of undesired output and weak disposal technology, the average environmental inefficiency of China's cement manufacturing industry is 0.1608, and the average efficiency is 0.8628, which is 23.9% higher than that of 0.6962 under the assumption of free disposal. This shows that in the study period, the strengthening of environmental regulation has indeed promoted the improvement of environmental efficiency of the cement manufacturing industry to a certain extent. On the other hand, at present, China's cement manufacturing industry can still achieve 16.08% output growth while the undesirable output of industrial smoke (dust) and sulfur dioxide is reduced by 16.08%. This shows that the effect of energy conservation and emission reduction policies formulated by the state for the cement industry in the recent 10 years has been obvious, but the overall environmental efficiency level of the cement manufacturing industry is not high, and there is still a lot of room for efficiency improvement in the future. (2) The average of environmental inefficiency under the assumption of undesired output weak disposal technology is 0.4462, and the difference between the two is 0.2854. This shows that the strict environmental regulation does bring a certain degree of efficiency loss (average efficiency loss is 28.54%) to China's cement manufacturing industry during the study period, resulting in an average compliance cost of CNY 23.414 billion. It can be seen that environmental regulation not only improves environmental efficiency, but also brings potential efficiency loss and compliance cost to the cement manufacturing industry. The optimal regulation design for the cement manufacturing industry needs to balance the advantages and disadvantages of the two, and explore the optimal regulation path between the minimum compliance cost and the maximum efficiency improvement.

Table 3. Calculation results of annual environmental efficiency and regulation efficiency loss of the cement manufacturing industry under two different disposal assumptions.

Year	Planning (3)		Planning (4)		*REL*	*ERC*
	γ_S	$1/(1+\gamma_S)$	β_W	$1/(1+\beta_W)$		
2004	0.4410	0.6940	0.1623	0.8604	0.2787	52.762
2005	0.4481	0.6906	0.1766	0.8499	0.2715	60.035
2006	0.3719	0.7289	0.1699	0.8548	0.2020	66.815
2007	0.5865	0.6303	0.2095	0.8268	0.3770	133.041
2008	0.7328	0.5771	0.2365	0.8087	0.4963	179.648
2009	0.4538	0.6879	0.2064	0.8289	0.2473	87.564
2010	0.2205	0.8193	0.1341	0.8818	0.0864	63.423
2011	0.4658	0.6822	0.1274	0.8870	0.3384	199.291
2012	0.4289	0.6999	0.2080	0.8278	0.2209	240.551
2013	0.5325	0.6525	0.1568	0.8644	0.3756	421.976
2014	0.4421	0.6934	0.0836	0.9229	0.3586	621.496
2015	0.3127	0.7618	0.1076	0.9028	0.2051	386.268
2016	0.3645	0.7328	0.1113	0.8999	0.2533	530.999
Mean	0.4462	0.6962	0.1608	0.8628	0.2854	234.144

From the calculation results of a single province in Tables 4 and 5, there are significant differences in the environmental efficiency of the cement manufacturing industry among different provinces and regions. (1) Under the assumption of free disposal, the average environmental inefficiency of the cement manufacturing industry above the national scale is 0.4462. Among them, the average environmental inefficiency of Shanghai, Jiangsu, Shandong, and other provinces is equal to zero, which indicates that the cement manufacturing industry in these provinces is at the forefront of production, and the production is the most efficient; while the average environmental inefficiency of Qinghai, Ningxia, Xinjiang, Yunnan, Guizhou, and other western provinces is more than 0.8, which leads to the serious imbalance between the development of the cement industry and the environment in these provinces, resulting in low environmental efficiency. From the regional calculation results, the average environmental inefficiency rate of the cement manufacturing industry in the eastern region is lower than the national average level, and the environmental efficiency is significantly better than that in the central and western regions. This shows that the economically developed eastern region has incomparable advantages in controlling pollution emissions and increasing desirable output compared with the central and western regions. (2) Under the assumption of weak disposal, the average environmental inefficiency rate of the cement manufacturing industry above the national scale decreased by 63.96% compared with the average environmental inefficiency rate under free disposal, which indicates that environmental regulation not only promotes the improvement of the environmental efficiency of the cement manufacturing industry, but also brings a certain degree of regulation efficiency loss. In addition to Shanghai, Jiangsu, Shandong, Beijing, Zhejiang, Hebei, and other provinces, the average of environmental inefficiency also dropped to zero under the constraint of weak disposal conditions, and the cement manufacturing industry in these six provinces is efficient. For the five western provinces with low environmental efficiency, the environmental efficiency has been improved to a certain extent under the constraint of weak disposal, which indicates that under certain investment conditions, the environmental efficiency has been improved. In this case, reducing the undesirable output such as smoke (dust) and sulfur dioxide can significantly improve the environmental efficiency of the cement manufacturing industry. (3) Under the constraint of a weak disposal assumption, the average environmental inefficiency of the cement manufacturing industry in the three regions decreased significantly. Among them, the central region has the largest decline, which is 70.78% lower than the average of environmental inefficiency under free disposal, showing a high level of efficiency. Under weak disposal, the average environmental inefficiency of the cement manufacturing industry in the eastern region is 0.0703, ranking first among the three regions; the average environmental inefficiency in the western region also drops to 0.2666, but it is still higher than the national average. This shows that in the underdeveloped areas of China and the west, due to the technical level, economic structure, energy structure, and other factors, there is still a serious waste of resources in the cement manufacturing industry, and the coordination between the cement industry and the environment is extremely unbalanced. These areas will be the key regulatory areas for the development of China's cement industry in the future.

4.2. Analysis of Compliance Cost and Regulation Efficiency Loss

According to the environmental efficiency scores under the above different assumptions, Table 6 gives the calculation data of regulation efficiency loss and compliance cost of the cement manufacturing industry in each province. During the research period, the average regulation efficiency loss of the cement manufacturing industry above the national scale is 28.54%, and the annual compliance cost reaches CNY 10.146 billion. Environmental regulation has a significant impact on the economic output of the cement industry. Among them, the average efficiency loss of the cement manufacturing industry in the western region is the largest, reaching 41.81%, which is far higher than the national average level; the central region shows higher environmental regulation costs, ranking first among the three regions. From the measurement results of a single province, the cement manufacturing industry of most provinces in China is still in non-DEA efficiency, and there are different degrees of regulation efficiency loss and compliance cost. In all provinces and cities, only Shanghai, Jiangsu, and Shandong have zero environmental inefficiency and zero compliance cost under two different disposal assumptions, which indicates that the coordination degree of the cement industry development and the environmental system in these provinces is high, and their actual production is at the forefront of production. Strict environmental regulation has little impact on output. On the contrary, the cement manufacturing industry in Qinghai, Jilin, Heilongjiang, Yunnan, Xinjiang, and other provinces shows higher regulation efficiency loss. Among them, the regulation efficiency loss of the Qinghai cement manufacturing industry ranks first in the country, reaching 119.9%; Hunan is the province with the largest compliance cost, with an average annual compliance cost of CNY 30.698 billion; Jilin, Guangdong, Chongqing, and Yunnan are also provinces with higher environmental regulation cost, with an average annual compliance cost of more than CNY 20 billion. The coordination degree of the cement industry development and the environmental system in these provinces is low, mainly relying on the bearing of natural resources.

Table 4. Calculation results of environmental efficiency of the provincial cement manufacturing industry under the assumption of free disposal.

Region	Province	2004	2006	2008	2010	2012	2014	2016	Mean
Eastern	Beijing	0.0000	0.0000	0.0000	0.0000	0.0000	0.1974	0.5511	0.0943
	Tianjin	0.5453	0.1487	1.0302	0.0000	0.0000	0.0000	0.0000	0.3378
	Hebei	0.0000	0.0000	0.0000	0.0000	0.0700	0.0000	0.0000	0.0054
	Liaoning	0.4133	0.6028	0.7779	0.4142	0.7003	0.6107	0.8039	0.6121
	Shanghai	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Jiangsu	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Zhejiang	0.0615	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0095
	Fujian	0.2911	0.2191	0.5832	0.4911	0.7504	0.1817	0.0000	0.3308
	Shandong	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Guangdong	0.0000	0.0000	0.2923	0.4514	0.2934	0.3634	0.4717	0.2052
	Hainan	0.0000	0.0000	1.8510	0.0000	0.9591	0.0000	0.0000	0.4325
Central	Shanxi	0.0000	0.5955	0.5216	0.9693	1.4939	0.0000	0.0000	0.6935
	Jilin	0.9351	1.1150	1.1018	0.0000	0.0273	1.5529	1.9399	0.7972
	Heilongjiang	1.1022	0.8686	1.3360	0.0000	0.7630	0.3246	0.2756	0.7564
	Anhui	0.6676	1.0920	0.7245	0.0000	0.0000	0.2397	0.0566	0.3626
	Jiangxi	1.0160	0.7895	0.6038	0.0000	0.0000	0.8019	0.3906	0.4740
	Henan	0.0755	0.1098	0.4237	0.0000	0.0000	0.0000	0.0000	0.0871
	Hubei	0.3668	0.3784	0.6155	0.0646	0.0771	0.4199	0.2992	0.3212
	Hunan	0.0000	0.0000	0.0000	0.0000	0.9362	0.6216	0.5986	0.3358
Western	Sichuan	0.3772	0.3668	0.7096	0.2102	0.3240	0.1833	0.2552	0.3190
	Chongqing	0.3173	0.0000	0.7911	0.0000	0.0000	0.9168	0.9029	0.6018
	Guizhou	0.9783	0.2435	0.8688	0.7834	1.5726	0.5647	0.4343	0.8187
	Yunnan	0.4409	0.6247	0.8185	0.5084	1.5762	0.8759	0.4099	0.8272
	Shaanxi	0.8927	0.9209	0.8290	0.1247	0.7966	0.6233	0.3187	0.6158
	Gansu	0.7090	0.5099	0.8494	0.0000	0.5000	0.6687	0.6390	0.5144
	Qinghai	1.8562	0.0000	2.2811	1.3782	0.0000	1.1827	0.5997	1.2624
	Ningxia	0.8197	0.7416	1.6839	1.2191	0.3960	0.7419	0.8500	0.9229
	Xinjiang	0.8296	0.8505	1.4107	0.0000	0.7842	1.4159	0.8549	0.9112
	Guangxi	0.0000	0.3751	0.8699	0.0000	0.8456	0.7770	0.2845	0.4141
	Inner Mongolia	0.5348	0.6051	1.0120	0.0000	0.0000	0.0000	0.0000	0.3244
	National average	0.4410	0.3719	0.7328	0.2205	0.4289	0.4421	0.3645	0.4462
	Eastern average	0.1192	0.0882	0.4122	0.1233	0.2521	0.1230	0.1661	0.1843
	Central average	0.5204	0.6186	0.6659	0.1292	0.4122	0.4951	0.4451	0.4785
	Western average	0.7501	0.4762	1.1022	0.3840	0.6177	0.7228	0.5045	0.6847

Note: Strictly speaking, the data in the table represent the environmental inefficiency value under free disposal, that is, the optimal solution of the directional distance function. The smaller the value is, the higher the environmental efficiency is. The value of zero means that the production unit is completely effective. Table 5 is the same.

Table 5. Calculation results of environmental efficiency of the provincial cement manufacturing industry under a weak disposal assumption.

Region	Province	2004	2006	2008	2010	2012	2014	2016	Mean
Eastern	Beijing	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Tianjin	0.0000	0.1028	0.0000	0.0000	0.0000	0.0000	0.0000	0.0722
	Hebei	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Liaoning	0.3913	0.3798	0.4784	0.3683	0.3659	0.4477	0.5092	0.4114
	Shanghai	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Jiangsu	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Zhejiang	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Fujian	0.0000	0.0000	0.1052	0.4182	0.5586	0.0551	0.0000	0.1492
	Shandong	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Guangdong	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1078	0.0083
	Hainan	0.0000	0.0000	0.0000	0.0000	0.8036	0.0000	0.0000	0.1317
Central	Shanxi	0.0000	0.5151	0.4435	0.6191	0.5124	0.0000	0.0000	0.4111
	Jilin	0.3854	0.3787	0.2745	0.0000	0.0000	0.0000	0.5061	0.1840
	Heilongjiang	0.3439	0.3816	0.4869	0.0000	0.0000	0.0000	0.0000	0.2051
	Anhui	0.0000	0.1232	0.0000	0.0000	0.0000	0.0000	0.0000	0.0156
	Jiangxi	0.0000	0.0000	0.0909	0.0000	0.0000	0.1147	0.1659	0.0683
	Henan	0.0629	0.0649	0.2947	0.0000	0.0000	0.0000	0.0000	0.0498
	Hubei	0.1684	0.1098	0.2430	0.0646	0.0000	0.0000	0.0520	0.1137
	Hunan	0.0000	0.0000	0.0000	0.0000	0.7099	0.0000	0.0709	0.0706
Western	Sichuan	0.2971	0.2833	0.4682	0.0000	0.0000	0.0225	0.0000	0.1392
	Chongqing	0.3169	0.0000	0.4321	0.0000	0.0000	0.0817	0.0816	0.1483
	Guizhou	0.6769	0.2301	0.4859	0.5911	0.7329	0.0000	0.0000	0.3852
	Yunnan	0.1716	0.2120	0.3196	0.2478	0.4934	0.0891	0.2157	0.2824
	Shaanxi	0.5652	0.5289	0.4156	0.1247	0.4881	0.3440	0.2684	0.3813
	Gansu	0.4439	0.3530	0.4018	0.0000	0.0000	0.4780	0.2934	0.2651
	Qinghai	0.0000	0.0000	0.0000	0.8248	0.0000	0.0000	0.0000	0.0634
	Ningxia	0.4053	0.3859	0.5673	0.7638	0.3199	0.0000	0.5877	0.4495
	Xinjiang	0.2184	0.3028	0.4825	0.0000	0.6044	0.5889	0.4768	0.3829
	Guangxi	0.0000	0.2492	0.4343	0.0000	0.6505	0.2854	0.0027	0.2114
	Inner Mongolia	0.4219	0.4949	0.6716	0.0000	0.0000	0.0000	0.0000	0.2236
	National average	0.1623	0.1699	0.2365	0.1341	0.2080	0.0836	0.1113	0.1608
	Eastern average	0.0356	0.0439	0.0530	0.0715	0.1571	0.0457	0.0561	0.0703
	Central average	0.1201	0.1967	0.2292	0.0855	0.1528	0.0143	0.0994	0.1398
	Western average	0.3197	0.2764	0.4254	0.2320	0.2990	0.1718	0.1751	0.2666

4.3. Regional Environmental Efficiency Analysis

The mean environmental inefficiency under two different disposal assumptions was tested respectively [24]. In Table 7, the results of the Kruskal–Wallis H test show that the environmental efficiency of the cement manufacturing industry in the eastern, central, and western regions has passed the 1% significance level test. The results of the Mann–Whitney U test of paired samples show that the environmental efficiency of the cement manufacturing industry in eastern and western regions, and eastern and central regions are significantly different at the level of 1% and 10%, respectively, while the environmental efficiency of the cement manufacturing industry in central and western regions under the assumption of free disposal does not pass the significance test. The results show that there are significant differences in the environmental efficiency of the cement manufacturing industry between different regions, and the degree of difference is closely related to the level of regional economic development. The eastern region has always been the fastest growing region of China's economy, with an incomparable location and technical advantages in the central and western regions, and so it has become the region with the highest environmental efficiency of the cement manufacturing industry. However, in the process of undertaking the industrial transfer from the eastern region, the midwest, which has the fastest growth rate of the cement manufacturing industry in recent years, is affected by technology, structure, and other factors, which restricts the absorption, digestion, and re-innovation ability of advanced technology in the midwest, resulting in significant differences between the environmental efficiency of the cement manufacturing industry in the midwest and the eastern region.

Table 6. Calculation results of regulation efficiency loss and compliance cost of the cement manufacturing industry in each province.

Region	Province	γ_S	β_W	*REL*	*ERC*
Eastern	Beijing	0.0943	0.0000	0.0943	13.310
	Tianjin	0.3378	0.0722	0.2656	11.474
	Hebei	0.0054	0.0000	0.0054	7.164
	Liaoning	0.6121	0.4114	0.2007	89.822
	Shanghai	0.0000	0.0000	0.0000	0.000
	Jiangsu	0.0000	0.0000	0.0000	0.000
	Zhejiang	0.0095	0.0000	0.0095	3.716
	Fujian	0.3308	0.1492	0.1816	65.307
	Shandong	0.0000	0.0000	0.0000	0.000
	Guangdong	0.2052	0.0083	0.1969	262.429
	Hainan	0.4325	0.1317	0.3008	16.489
Central	Shanxi	0.6935	0.4111	0.2824	56.617
	Jilin	0.7972	0.1840	0.6132	205.273
	Heilongjiang	0.7564	0.2051	0.5513	114.147
	Anhui	0.3626	0.0156	0.3470	137.903
	Jiangxi	0.4740	0.0683	0.4057	169.598
	Henan	0.0871	0.0498	0.0373	19.070
	Hubei	0.3212	0.1137	0.2075	167.146
	Hunan	0.3358	0.0706	0.2652	306.983
Western	Sichuan	0.3190	0.1392	0.1798	184.521
	Chongqing	0.6018	0.1483	0.4535	234.952
	Guizhou	0.8187	0.3852	0.4335	151.778
	Yunnan	0.8272	0.2824	0.5448	252.294
	Shaanxi	0.6158	0.3813	0.2345	88.807
	Gansu	0.5144	0.2651	0.2493	69.839
	Qinghai	1.2624	0.0634	1.1990	69.530
	Ningxia	0.9229	0.4495	0.4734	45.522
	Xinjiang	0.9112	0.3829	0.5283	120.971
	Guangxi	0.4141	0.2114	0.2027	170.304
	Inner Mongolia	0.3244	0.2236	0.1008	8.901
	National average	0.4462	0.1608	0.2854	101.462
	Eastern average	0.1843	0.0703	0.1140	42.701
	Central average	0.4785	0.1398	0.3387	147.092
	Western average	0.6847	0.2666	0.4181	127.038

Table 7. Regional difference test results of environmental efficiency.

Model	Test Method	Region	Mean Environmental Inefficiency	Regional Comparison	*p*
Planning (3)	Mann–Whitney U	Eastern	0.1843	East and Central	0.0208 **
	Mann–Whitney U	Central	0.4785	Central and Western	0.1372
	Mann–Whitney U	Western	0.6845	West and East	0.0014 ***
	Kruskal–Wallis H	Nationwide	0.4462	East, Central, and West	0.0022 ***
Planning (4)	Mann–Whitney U	Eastern	0.0703	East and Central	0.0631 *
	Mann–Whitney U	Central	0.1398	Central and Western	0.0390 **
	Mann–Whitney U	Western	0.2666	West and East	0.0028 ***
	Kruskal–Wallis H	Nationwide	0.1608	East, Central, and West	0.0036 ***

Note: Mann–Whitney U test is the accurate one-sided significance level, and the Kruskal–Wallis H test is the progressive significance level. * Significant at 10% level; ** Significant at 5% level; *** Significant at 1% level.

5. Conclusions and Policy Implication

Using the input–output and pollution emission data of the cement manufacturing industry in 30 provinces in China, this paper constructs a directional distance function model based on panel data and uses the nonparametric DEA method to comprehensively calculate the environmental efficiency, regulation efficiency loss, and compliance cost of the cement manufacturing industry in China by year and region for the first time under two different technical assumptions. Our research found that, as a traditional industrial sector with high pollution, high energy consumption, and high emissions, the cement manufacturing industry is still a burden on the improvement of China's overall industrial environmental efficiency. This situation had not gradually changed until 2005. Over the past 10 years, the inefficiency level of China's cement manufacturing industry has shown a downward trend year by year. The Chinese government's strengthening of environmental governance has improved the environmental efficiency of the cement manufacturing industry to a certain extent, but the overall efficiency level is not high, and there is still a lot of room for improvement. Government environmental regulation is a "double-edged sword" [25]. It not only improves the environmental efficiency of the cement manufacturing industry, but also brings a certain degree of efficiency loss and compliance cost to China's cement manufacturing industry. There are significant differences between different regions. The regulation cost of the cement manufacturing industry in central and western regions is significantly higher than that in eastern regions.

According to the analysis results of this study, it is suggested that policymakers and officials should follow the principle of step-by-step for a long time into the future, and take flexible regulatory measures according to the development trend of China's cement industry while maintaining the continuity of existing policies. At present, the environmental regulation for China's cement industry focuses on emission reductions. Forcing cement manufacturing enterprises to carry out technological innovation through mandatory emission reductions will be an effective method. When designing the optimal regulation policy, government departments need to comprehensively weigh various advantages and disadvantages and explore the optimal path of environmental regulation between minimizing the cost of compliance and maximizing the improvement of efficiency. Therefore, on the one hand, government departments should establish a sound incentive mechanism for cleaner production to guide cement enterprises to transform from end-to-end governance to cleaner production. On the other hand, it is necessary to strengthen the construction of the ecological cement industry and use the concept of a circular economy to build an ecological cement industry chain.

Formulating regulatory policies according to regional differences will be more conducive to the win–win development of China's cement industry. The eastern region, which is sensitive to environmental regulation, can consider carefully relaxing the regulation policy to reduce the negative impact of regulation on output, and strengthen environmental supervision and law enforcement to prevent opportunism. For the central and western regions that are not sensitive to regulation response, it is more appropriate to take steadily strengthened environmental regulation measures, forcing cement enterprises in this region to actively carry out technological innovation to reduce pollutant emissions.

Due to the influence of many subjective and objective factors, this research still has identified a number of limitations, which need to be further explored in the follow-up research. Firstly, the current statistical data specifically for the cement manufacturing industry are not comprehensive and the quality is not high, so it is difficult to obtain the statistical data of enterprises below the scale. Secondly, although based on the existing research, this paper extends from the macroeconomic level to the mesoeconomic level, integrating the material flow analysis at the industrial technology level, and the value flow analysis at the economic level, and so evaluating and analyzing the micro effect will be an important research topic in the future. Thirdly, this paper only selects sample data from 2004 to 2016, and the research conclusion only represents the basic situation of China's cement industry's environmental efficiency during this period. It is also necessary to investigate the changes of the cement industry's environmental efficiency from a dynamic perspective according to China's economic development track, which will be the next direction worthy of research. Despite these limitations, this paper makes an important contribution to research on the environmental efficiency of China's cement manufacturing industry.

Author Contributions: All authors contributed to the study conception and design. H.T. provided the idea for this research work. Material preparation and data collection and analysis were performed by W.D. and X.X. The first draft of the manuscript was written by H.T. and W.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by the National Social Science Fund of China (No.21BGL085), Research Center for Mining and Metallurgy Culture and Socio-economic Development in the Middle Reaches of Yangtze River Foundation (No. 2014kyb06).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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