sustainability

MDPI

Article

Sustainability Assessment of Refining Enterprises Using a DEA-Based Model

Hui Li [1,2], Kangyin Dong [1,3], Renjin Sun [1,*], Jintao Yu [4] and Jinhong Xu [5]

1 School of Business Administration, China University of Petroleum (Beijing), Beijing 102249, China; cuphli@163.com (H.L.); dongkangyin@163.com (K.D.)
2 Energy Systems Research Center, The University of Texas at Arlington, Arlington, TX 76019, USA
3 Department of Agricultural, Food and Resource Economics, Rutgers, The State University of New Jersey, New Brunswick, NJ 08901, USA
4 China National Nuclear Corporation, 1 Nansanxiang, Sanlihe, Xicheng District, P.O.Box 2101-2, Beijing 100822, China; yujt@cnnc.com.cn
5 CNPC Economics and Technology Research Institute, Beijing 100724, China; xujinhong@cnpc.com.cn
* Correspondence: sunrenjin@cup.edu.cn; Tel.: +86-10-5114-1501

Academic Editor: Tomonobu Senjyu
Received: 26 February 2017; Accepted: 13 April 2017; Published: 16 April 2017

Abstract: As one of the basic industries supporting the national economy development and energy demand, the refining industry is expected to provide combustion energy, reduce pollution emission, and improve utilization efficiency. With more stringent requirement for environmental protection, refining enterprises have to insist on the sustainable development to achieve industrial optimization. Evaluation of the sustainability of enterprises can help them understand their situation more objectively and guide them to establish modes for sustainable development. In this study, the evaluation system is firstly built from perspectives of economic, ecological, and social sustainability, including six second-grade indexes and seventeen third-grade indexes, which can accurately reflect the entire sustainability contents of refining enterprises. Then, a DEA-based model is constructed, which selects seven input indexes (e.g., the asset–liability ratio and comprehensive energy consumption per unit of output) and nine output indexes (e.g., return on assets, asset turnover, and science and technology investment strength). The DEA-based model can not only objectively evaluate the sustainability level, but also find out the restriction factors for further optimization. Third, to demonstrate the validity of the model, 15 enterprises are selected for case studies, among which only four are identified as having strong sustainability. For the other 11 enterprises, projection analyses are implemented, and the DMU values of three enterprises characterized by low efficiency are adjusted to find out the restriction factors, which reflect the model's efficiency and its potentially wide application in the future. Finally, specific suggestions are proposed for the enhancement of sustainability of refining enterprises.

Keywords: refining enterprise; sustainability assessment; data envelopment analysis; policy recommendations

1. Introduction

Dealing with the relationship between resources and the environment has been recognized as a common problem facing humans. Sustainable development is the only way to coordinate the harmonious development of human, nature, and society [1]. The refining industry, as a basic industry meeting the national demand of energy, is confronted with the tasks of providing combustion energy as well as reducing emissions [2]. China's oil refining industry has been rapidly developed, specifically reflecting the sustained growth in the aspects of capacity and production, integrated large-scale equipment, the integration of refining and chemical processes, and high industry clustering [3]. By the end of 2015, the refining capacity of China's oil industry reached 710 million tons/year, with an increasing capacity of 30.2 million tons/year [4]. However, it should also be noted that oil refining enterprises, contributing to large amounts of energy consumption and emissions, are also experiencing severe environmental pressure. Among the top 1000 energy-consuming enterprises in China, 340 petrochemical enterprises account for more than a third. There are 482 petroleum enterprises and 803 chemical enterprises in the key waste water pollution monitoring list, accounting for 13.4% and 25.8%, respectively [4]. According to the goal proposed in the "13th Five-Year Plan", the amount of industrial energy consumption and CO_2 emission per 10 thousand yuan of added value should be 10% lower by 2020 [5]. This could be a substantial challenge for the refinery enterprises that are now suffering a low oil price hit. It is definitely unsustainable for refinery enterprises to develop the economy at the expense of resources in the current situation characterized by weak demand, overcapacity, enhanced oil specification, and strict environmental protection requirements [6]. Therefore, the sustainable development of the oil refining industry should be realized through the unification of economic, social, and environmental benefits as well as the harmonious development of resources, the environment, and enterprises [7].

To solve the current problem and realize sustainable development, oil refining enterprises should highlight energy-saving, low carbon emissions, and a green environment [8]. Oil refining enterprises should appropriately evaluate the sustainability of their development, which can not only help enterprises to gain an objective knowledge of their present situation, but also help put forward countermeasures and suggestions to guide and promote the concrete practice of sustainable development [9]. Evaluations of the sustainability of enterprises at home and abroad have made abundant research achievements. Common evaluation methods used in sustainability evaluations mainly include the Delphi method, the analytic hierarchy process, grey correlation analysis, principal component analysis, and so on [10–13]. These methods first determine the index weight, and then obtain the evaluation results through a weighted average calculation. They are favored by their relatively scientific and comprehensive reflection of sustainability of specific research objects, which result from systematic and reasonable index weight determination and a suitable index system setting. Each method has advantages and disadvantages, and there is significant controversy over which method is superior, but all have been proven to be useful in assessing sustainability. However, if we want to adjust and improve the sustainability performance further, it is essential to find out affecting factors. Such guidance information of optimization is significant for refining enterprises [14].

When it comes to the evaluation of sustainability of oil refining enterprises, there are limited related researches. Jia et al. (2003) established an evaluation index system from perspectives of economy, society, science and technology, environment, and resources, in which an analytic hierarchy process was used to determine index weight, while a BP neural network was applied to test the model's feasibility and scientificity [15]. Lv et al. (2007) built up an evaluation index system consisting of 5 second-grade indexes and 21 third-grade indexes from aspects of the present development situation and the sustainable development potential [16]. Dong et al. (2015) constructed a model from dimensions of economy, resource utilization, clean production, and 3R level, as well as environmental impact, and evaluated the index system using DHGF integration means [17]. However, these works did not fully address the aforementioned shortcomings. Data envelopment analysis (DEA), a method evaluating the relative effectiveness of the system with multiple input and output indexes from the angle of input and output, has been proposed to not only provide objective and accurate evaluation results for each decision-making unit but also put forward specific improvement schemes through projection analysis for the decision-making unit insensitive to the scale technology [18,19]. There are many advantages to using the DEA method to evaluate the sustainable development of oil refining enterprises. First of all, DEA can well handle the complex system of the sustainable development, which is a dynamic system with multiple inputs and outputs [20]. Second, the index system evaluating refineries' sustainability involves multiple indexes with non-unified dimensions, which do not need to be considered in the DEA [21]. Moreover, relatively effective and ineffective decision-making units can be distinguished by DEA, and the gap between ineffective and ideal decision units can also be identified, which can provide refining enterprises with specific improvement schemes, target values, and adjusted values [22]. This paper aims to construct a comprehensive evaluation index system for oil refining enterprises based on DEA by integrating subjective and objective weights to generate the input and output indexes, which will possibly help enterprises to gain new ideas for the evaluation of their sustainability. The research framework is shown in Figure 1.

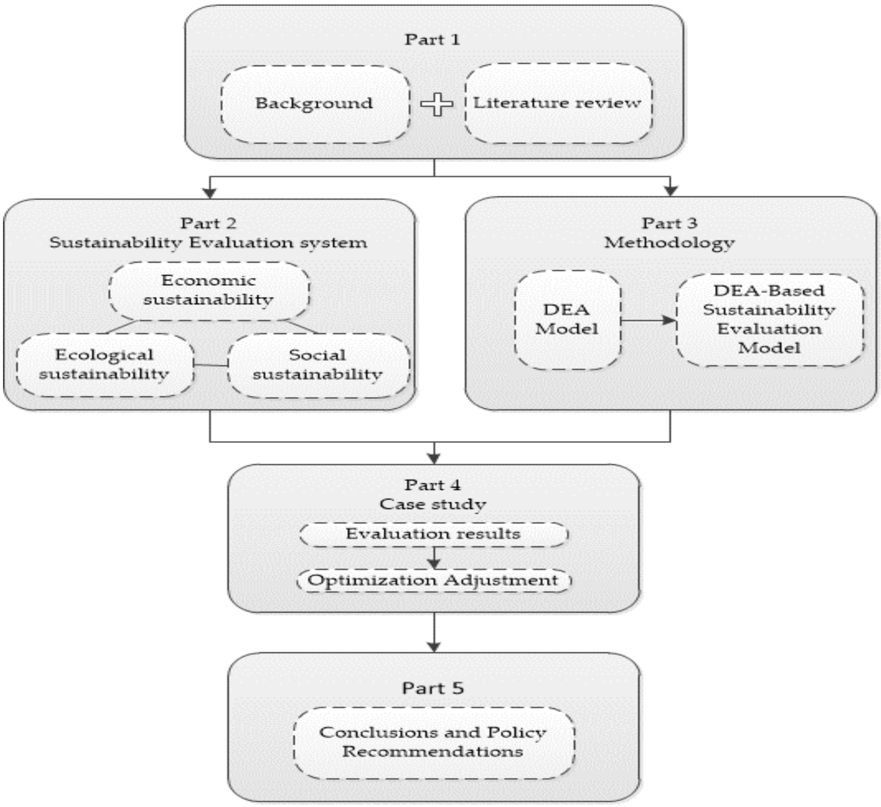

Figure 1. Research framework of sustainable assessment of refining enterprises.

2. Establishment of a Refining Enterprise Sustainability Evaluation Index

2.1. Selection Princple

The sustainability of refining enterprises is attributed to the common efforts of internal and external factors, and it is characterized by openness, complexity, and dynamics. The composition of the evaluation index system is very complex, and several principles should be followed in the index selection [23–25]. The first principle is the systematicness, which highlights that selected indexes should be able to reflect the connotation of sustainability, including economic, ecological, and social sustainability. The second principle is the scientificity, which means that selected indexes should be able to objectively reflect the development status of the involved system during the development as well as the interaction among systems. Then comes the dominant principle, which requires the indexes to truly reflect the sustainable development potential of oil refining enterprises. The fourth principle is dynamics, which means selected indexes should be able to reflect both the current situation and future trends. The last principles are conciseness, comparability, and operability, which highlight the consistency of evaluation content complexity and evaluation index simplicity, and the indexes should be comparable and easily available to comprehensively reflect the connotation of sustainability.

2.2. Sustainability Index System Establishment

Concerning the sustainability in the energy sector, Johnstone et al. (2017) explored the relationship among environmental regulation, innovation, and competitiveness. It showed that the stringent environmental regulations have a positive effect on firms' efficiency improvements [26]. By using data envelopment analysis, Yagi et al. (2015) indicated that the environmental, social, and governance activities of firms do not considerably affect environmental efficiency [27]. Fujii (2015) proposed optimal production resources reallocation to reduce CO_2 emission based on data envelopment analysis [28]. While the sustainability of oil refining enterprises consists of the economic, ecological, and social sustainability. Among them, the economic sustainability is the foundation [29], the ecological sustainability is the inevitable requirement [30], and the social sustainability is the powerful guarantee [31].

2.2.1. Economic Sustainability Index

The economic sustainability evaluation index is designed considering the present situation and the potential. Business performance is selected to reflect the present situation, while scientific research and innovation ability is used to reflect the potential [32,33].

(1) The business performance evaluation index refers to the enterprise management benefit and operator performance during certain operation period, which can reflect the present situation of an enterprise, and its evaluation indexes mainly include the return on assets, asset–liability ratio, and asset turnover [34]. Return on assets is the ratio of the earnings before interest and tax over the average total assets during a certain period, which can measure the comprehensive efficiency of economic resources of an enterprise; asset–liability ratio refers to the ratio of current debt and total assets, which serves as a measure of the debt level and business risk of enterprise; and asset turnover is the ratio of the current main business income and average total assets, which can be used to measure the asset operation efficiency.

(2) Scientific research and innovation ability is generally used to evaluate an enterprise's sustainability potential, as it can guarantee the vitality of an enterprise. Selected indexes include R&D investment strength and R&D personnel proportion [35]. R&D investment intensity refers to the ratio of current R&D investment to sales revenue, and the proportion of R&D personnel refers to the ratio of current R&D personnel to the average total staff during that period.

2.2.2. Ecological Sustainability Index

Refining enterprises are characterized by high energy consumption and pollution, and thus it is critical for them to highlight the rational use of resources, the investment in the environmental protection, and the control of pollution. Two categories of indexes are thought to influence the ecological sustainability, namely the resource utilization efficiency index and the environmental protection investment and pollution control index [36,37].

(1) Resource utilization efficiency refers to the utilization degree of raw materials, fuels, and auxiliary materials in the process of production. The evaluation index includes the comprehensive energy consumption per unit of output, entire cost per unit, and comprehensive commodity rate [38]. Comprehensive energy consumption per unit of output reflects the energy consumption of oil refinery enterprises in the process of production. Lower values indicate higher efficiency. The entire cost per unit is the ratio of the total operation cost to the crude oil processing capacity, which reflects the costs of enterprise when processing per unit of raw materials. The comprehensive commodity rate is the ratio of crude oil products over the crude oil processing capacity, and it reflects the refining efficiency of crude oil resources.

(2) The environmental protection investment and pollution control index can comprehensively reflect the investment in enterprise environmental protection, the control ability of "three wastes"

emissions, and the treatment ability of "three wastes" [39]. Evaluation indexes include environmental protection investment per 10 thousand yuan output, solid waste emissions per unit of output, wastewater emissions per unit of output, waste gas emissions per unit of output, and the standard volume of "three wastes" emission. The environmental protection investment per 10 thousand yuan output refers to the average environmental protection cost per 10 thousand yuan of output during certain period; solid waste/water/gas emissions per unit of output refers to the ratio of solid waste/water/gas emissions over the total enterprise output; and "three wastes" disposal rate refers to the average of the disposal rates of waste solid, water, and gas.

2.2.3. Social Sustainability Evaluation Index

Oil refining enterprises should actively repay society, participate in the public welfare, and shoulder the social responsibility while pursuing economic and environmental benefits. The evaluation of their social sustainability is actually the evaluation of their capacities to fulfill social obligations and deal with corresponding effects, which can be specifically evaluated by social contribution ability and worker protection ability [40,41].

(1) Social contribution ability intuitively reflects the contribution of an enterprise to the society, which can be expressed by the social contribution rate and the social accumulation rate [42]. The former concept is the ratio of an enterprise's contribution to society to its average total assets, and thus it can measure the capacity of an enterprise to contribute to the society with all the assets. The latter concept refers to the ratio of the total fiscal revenue to the contribution to the society, and it can measure the support degree of an enterprise to the social public welfare.

(2) The worker protection ability mainly refers to the guarantee of enterprises towards workers concerning their basic life demand and stable employment. Good corporate culture requires the unity of the workers, so that the guarantee of basic life demand and employment is provided. It is generally evaluated by the income per capita and the employee turnover rate [43]. Income per capita is the ratio of the current total wages to the total number of employees, which can reflect the level of the employees' basic needs. The employee turnover rate is the ratio of the number of leaving employees to the total number of employees during a certain period, which represents employment stability.

Therefore, the sustainable development evaluation index system for oil refining enterprises is established, as shown in Figure 2.

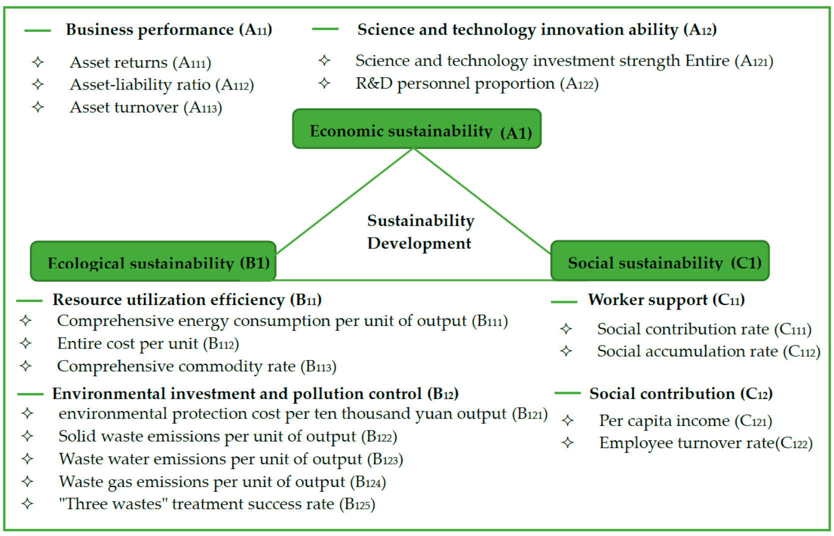

Figure 2. Sustainable development evaluation index system for oil refining enterprises.

3. Methodology

3.1. DEA Model

A DEA-based model was developed and established according to the concept of "relatively effective evaluation" to achieve the system analysis. The production function, which highlights multiple inputs and outputs, can significantly reduce the error due to unnecessary parameter estimation, and thus effectively avoid subjective factors and simplify the algorithm [44]. The DEA-based model can be expressed as follows:

$$\begin{cases} \min\theta \\ s.t. \sum_{i=1}^{n} \lambda_i x_i + S^- = \theta X_0 \\ \sum_{i=1}^{n} \lambda_i y_i - S^+ = y_0 \\ \lambda_i \geq 0, i = 1,2,3,\cdots,\text{n} \\ s^- \geq 0, s^+ \geq 0 \end{cases} \quad (1)$$

where θ is the integrated sustainability evaluation value, X is the input index, Y is the output index, S^- is the residual variable, and S^+ is the slack variable.

When $\theta_0 = 1$ and $S^- = S^+ = 0$, we consider the DMU as technically and scaly efficient; when $\theta_0 \prec 1$ and $S^- \neq 0, S^+ \neq 0$, we consider the DMU as either technically or scaly inefficient. When the DMU is inefficient, we can improve the decision-making units by projecting the DMU on the relatively effective plane.

3.2. The DEA-Based Sustainbility Evaluation Model

The efficiency of DEA model depends on the input and output variables exploration [45]. Therefore, it is necessary to select the appropriate variables to ensure the discriminatory power of the DEA model. As is known, input and output indexes refer to the "pain" and "gain" for an enterprise. Therefore, they are the most critical factors affecting the enterprise's development [46]. The selection of them is the precondition of the DEA model, and the selection should follow the following principles [47]: The first is the evaluation goal. Selected indexes should be able to attain the goal of evaluation and fully reflect the evaluation's purpose. That is, factors that have significant effects on the evaluation's purpose should be included. The second principle is authenticity, which means that the selection should comply with the actual situation, and individual subjective influence should be eliminated. Third is relevance. The relationship between input and output indexes should be taken into account. Attention must be paid to avoid the strongly linearly correlated indexes, because the information could be largely contained within each other. Fourth is accessibility. Whether we can obtain enough information and related data needs to be considered.

In this study, 15 domestic refining enterprises of the PetroChina and Sinopec are selected for DEA-based sustainability analysis according to the 2015 yearbook and other related information (Table 1). In addition to the above principles, smaller input values and larger output values are preferred [48]. Since a strong linear relationship should be avoided, correlation analysis was employed, and the results are shown in Table 2. It is noted that the return on assets is strongly correlated with the social accumulation rate. Considering the comprehensive influence of the return on assets, we abandon the social accumulation rate index. Therefore, there are finally 16 input and output indexes, and the following specific indexes are selected:

Input indexes: asset–liability ratio, comprehensive energy consumption per unit of output, entire cost per unit, solid waste emissions per unit of output, wastewater emissions per unit of output, waste gas emissions per unit of output, and employee turnover rate.

Table 1. Input–output indexes concerning the sustainability of 15 refining enterprises.

	JX	DL	FS	LZ	YS	ZH	YZ	JL	MM	TJ	QL	GZ	GQ	FJ	Z
A_{111}	−22.13	−40.66	−26.97	−18.12	−8.35	−5.97	−10.58	−13.39	−1.46	−78.57	−9.15	−29.11	−26.26	−19.05	−1.46
A_{112}	8.96	21.29	19.2	19.34	1.03	22.83	20.1	16.4	13.77	27.93	13.17	4.39	2.37	23.33	1.03
A_{113}	1.44	1.85	1.72	1.83	2.22	3.38	2.19	3.97	5	2.26	2.87	3.74	3.46	3.31	5
A_{121}	0.86	1.56	0.45	1.44	1.62	2.06	2.97	2.13	1.91	0.93	1.19	1.53	1.12	1.25	2.97
A_{122}	15.78	19.41	17.26	20.61	23.9	15.5	27.5	13.73	17.04	14.25	15.37	19.09	14.72	23.21	27.5
B_{111}	0.32	0.32	0.36	0.34	0.31	0.48	1.4	0.34	0.26	0.3	0.42	0.74	0.38	0.36	0.26
B_{112}	222.3	83.63	98.41	159.7	187.6	89.65	139.6	159.8	156.3	155.3	166.6	162.8	188.7	265.3	83.63
B_{113}	92.79	90.64	92.02	93.37	94	95.94	93.95	93.98	94.7	95.51	95.1	93.49	94.87	92.41	95.94
B_{121}	23.17	25.86	115.4	165.7	78.34	36.14	38.37	242.5	89.87	36.07	89.15	167.2	88.69	3.94	242.5
B_{122}	0.2	0	1.7	0.85	0.6	0.25	5.16	2.68	0.42	1.7	0	12.54	3.37	0	0
B_{123}	0.59	0.06	0.86	0.33	0.5	0.49	0.49	0.58	0.69	0.95	1.14	0.79	0.42	0.87	0.06
B_{124}	0.58	0.24	1.29	0.37	0.54	0.35	0.06	1.73	0.49	0.17	0.86	0.9	0.83	0.26	0.06
B_{125}	99.81	98.95	100	99.15	99.26	100	99.27	99.04	100	97.48	97.55	99.05	97.57	100	100
C_{111}	7.81	1.55	11.6	10.94	9.57	10.9	7.3	12.11	20.89	1.62	14.19	12.59	10.62	0.43	20.89
C_{112}	54.45	49.15	50.03	42.94	61.96	80.8	43.93	68.5	76.43	−312.6	45.24	70.7	67.13	29.5	80.8
C_{121}	62,615	70,712	7601	77,449	72,953	82,566	81,508	65,143	75,861	56,957	47,099	90,382	81,931	75,865	90,382
C_{122}	7.36	11.8	10.61	5.21	4.38	11.43	8.77	6.92	6.15	8.18	8.9	4.22	5.94	7.99	4.22

Note: A_{111}: asset returns (%); A_{113}: asset–liability ratio (%); A_{113}: asset turnover (%); A_{121}: science and technology investment strength entire (%); A_{122}: R&D personnel proportion (%); B_{111}: comprehensive energy consumption per unit of output (tons of standard coal per million yuan); B_{112}: entire cost per unit (ton per yuan); B_{113}: comprehensive commodity rate (%); B_{121}: environmental protection cost per 10 thousand yuan output (yuan); B_{122}: solid waste emissions per unit of output (kilogram per million yuan); B_{123}: waste water emissions per unit of output (ton per million yuan); B_{124}: waste gas emissions per unit of output (million cubic meters/million yuan); B_{125}: "Three wastes" treatment success rate (%); C_{111}: social contribution rate (%); C_{112}: social accumulation rate (%); C_{121}: per capita income (yuan); C_{122}: employee turnover rate (%).

Table 2. Correlation analysis of input and output indexes.

	A_{111}	A_{112}	A_{113}	A_{121}	A_{121}	B_{111}	B_{112}	B_{113}	B_{121}	B_{122}	B_{123}	B_{124}	B_{125}	C_{111}	C_{112}	C_{131}	C_{122}
A_{111}	1.00	−0.42	0.43	0.52	0.36	0.12	−0.02	0.20	0.30	−0.15	−0.22	0.09	0.53	0.65	0.85	0.32	−0.23
A_{112}	−0.42	1.00	−0.34	−0.16	−0.21	0.11	−0.11	−0.21	−0.44	−0.25	0.26	−0.17	0.00	−0.56	−0.49	−0.33	0.669
A_{113}	0.43	−0.34	1.00	0.52	0.06	−0.14	−0.09	0.55	0.50	0.12	−0.07	0.07	0.16	0.65	0.27	0.38	−0.41
A_{121}	0.52	−0.16	0.52	1.00	0.60	0.45	−0.36	0.38	0.34	0.09	−0.53	−0.33	0.29	0.37	0.31	0.46	−0.21
A_{122}	0.36	−0.21	0.06	0.60	1.00	0.41	−0.07	−0.09	0.07	0.04	−0.43	−0.56	0.42	0.04	0.25	0.52	−0.29
B_{111}	0.12	0.11	−0.14	0.45	0.41	1.00	−0.06	0.00	−0.16	0.57	0.04	−0.17	0.00	−0.12	0.10	0.28	0.11
B_{112}	−0.02	−0.11	−0.09	−0.36	−0.07	−0.06	1.00	−0.12	−0.29	0.03	0.44	0.08	−0.12	−0.32	−0.07	−0.26	−0.36
B_{113}	0.20	−0.21	0.55	0.38	−0.09	0.00	−0.12	1.00	0.25	−0.03	0.11	−0.14	−0.25	0.50	−0.19	0.03	−0.31
B_{121}	0.30	−0.44	0.50	0.34	0.07	−0.16	−0.29	0.25	1.00	0.26	−0.23	0.46	0.06	0.66	0.28	0.28	−0.56
B_{122}	−0.15	−0.25	0.12	0.09	0.04	0.57	0.03	−0.03	0.26	1.00	0.16	0.25	−0.16	0.05	0.05	0.42	−0.32
B_{123}	−0.22	0.26	−0.07	−0.53	−0.43	0.04	0.44	0.11	−0.23	0.16	1.00	0.34	−0.29	−0.11	−0.37	−0.53	0.12
B_{124}	0.09	−0.17	0.07	−0.33	−0.56	−0.17	0.08	−0.14	0.46	0.25	0.34	1.00	−0.11	0.24	0.26	−0.21	−0.03
B_{125}	0.53	0.00	0.16	0.29	0.42	0.00	−0.12	−0.25	0.06	−0.16	−0.29	−0.11	1.00	0.23	0.51	0.51	0.02
C_{111}	0.65	−0.56	0.65	0.37	0.04	−0.12	−0.32	0.50	0.66	0.05	−0.11	0.24	0.23	1.00	0.28	0.37	−0.45
C_{112}	0.85	−0.49	0.27	0.31	0.25	0.10	−0.07	−0.19	0.28	0.05	−0.37	0.26	0.51	0.28	1.00	0.53	−0.12
C_{121}	0.32	−0.33	0.38	0.46	0.52	0.28	−0.26	0.03	0.28	0.42	−0.53	−0.21	0.51	0.37	0.53	1.00	−0.32
C_{122}	−0.23	0.69	−0.41	−0.21	−0.29	0.11	−0.36	−0.31	−0.56	−0.32	0.12	−0.03	0.02	−0.45	−0.12	−0.32	1.00

Output indexes: return on assets, asset turnover, investment intensity in science and technology, R&A personnel, comprehensive commodity rate, environmental protection cost per 10 thousand yuan of output, "three wastes" disposal rates, social contribution rate, and income per capital.

In the evaluation of n DMUs, x_{ij} are used to represent the m input indexes. Then, the input of $DMU_j (1 \le j \le n)$ can be expressed as

$$x_{ij} = (x_{1j}, x_{2j}, \cdots, x_{mj})^T \quad (i = 1, 2, \cdots, m).$$

Similarly, y_{rj} are used to represent the s output indexes, and the output of DMU_j can thus be expressed as

$$y_{rj} = (y_{1j}, y_{2j}, \cdots, y_{sj})^T \quad (r = 1, 2, \cdots, s).$$

In this condition, the DEA-based sustainability evaluation model is constructed:

$$\begin{cases} \min\theta \\ s.t. 8.96\lambda_1 + 21.29\lambda_2 + 19.20\lambda_3 + 19.34\lambda_4 + 1.03\lambda_5 + \cdots + 1.03\lambda_{15} + s_1^- = 8.96\theta \\ 222.30\lambda_1 + 80.63\lambda_2 + 98.41\lambda_3 + 159.72\lambda_4 + 187.65\lambda_5 + \cdots + 83.63\lambda_{15} + s_2^- = 222.30\theta \\ 0.32\lambda_1 + 0.32\lambda_2 + 0,36\lambda_3 + 0.34\lambda_4 + 0.31\lambda_5 + \cdots + 0.26\lambda_{15} + s_3^- = 0.32\theta \\ \quad \vdots \ \cdots \ \vdots \ \cdots \ \vdots \ \cdots \ \vdots \ \cdots \ \vdots \ \cdots \ \vdots \ \cdots \ \vdots \ \cdots \ \vdots \\ 7.26\lambda_1 + 11.80\lambda_2 + 10.61\lambda_3 + 5.21\lambda_4 + 4.38\lambda_5 + \cdots + 4.22\lambda_{15} + s_7^- = 7.26\theta \\ -22.13\lambda_1 + (-40.66)\lambda_2 + (-26.97)\lambda_3 + (-18.12)\lambda_4 + (-8.35)\lambda_5 + \cdots + (-1.46)\lambda_{15} - s_1^+ = -22.13 \\ 1.44\lambda_1 + 1.85\lambda_2 + 1.72\lambda_3 + 1.83\lambda_4 + 2.22\lambda_5 + \cdots + 5.00\lambda_{15} - s_2^+ = 1.44 \\ 0.86\lambda_1 + 1.56\lambda_2 + 0.45\lambda_3 + 1.44\lambda_4 + 1.62\lambda_5 + \cdots + 2.97\lambda_{15} - s_3^+ = 0.86 \\ \quad \vdots \ \cdots \ \vdots \ \cdots \ \vdots \ \cdots \ \vdots \ \cdots \ \vdots \ \cdots \ \vdots \ \cdots \ \vdots \ \cdots \ \vdots \\ 7.81\lambda_1 + 1.55\lambda_2 + 11.6\lambda_3 + 10.9\lambda_4 + 9.57\lambda_5 + \cdots + 20.8\lambda_{15} - s_9^+ = 7.81 \\ \lambda_i > 0, i = 1, 2, 3, \cdots, 15 \\ s^- \ge 0, s^+ \ge 0 \end{cases} . \quad (2)$$

4. Results and Discussion

As shown in Table 3, there are four enterprises demonstrated to be both technically and scaly efficient, and thus they have relatively stronger sustainability. The other 11 enterprises are relatively not technically or scaly efficient, which might be due to certain indexes concerning economic, ecological, and social sustainability. Countermeasures for the 11 enterprises should be specifically put forward.

Table 3. DEA-based relative effectiveness evaluation results.

Enterprises	Ranking	Relative Efficiency	Scale and Technical Efficiency
Z	1	1	Scaly and technically efficient
YZ	1	1	Scaly and technically efficient
MM	1	1	Scaly and technically efficient
GZ	1	1	Scaly and technically efficient
YS	5	0.9926	Scaly and technically inefficient
DL	6	0.9895	Scaly and technically inefficient
ZH	7	0.93285	Scaly and technically inefficient
TJ	8	0.861589	Scaly and technically inefficient
FS	9	0.849812	Scaly and technically inefficient
LZ	10	0.803096	Scaly and technically inefficient
JX	11	0.7972417	Scaly and technically inefficient
JL	12	0.7480421	Scaly and technically inefficient
FJ	13	0.7055672	Scaly and technically inefficient
GQ	14	0.7025143	Scaly and technically inefficient
QL	15	0.6032789	Scaly and technically inefficient

Projection analyses are conducted for the 11 enterprises that DEA is not applicable and that are scaly ineffective, which bring the slack variable values as shown in Table 4.

Table 4. Slack variable values of the 11 enterprises.

Enterprises		**JX**	**DL**	**FS**	**LZ**	**YS**	**ZH**	**JL**	**TJ**	**QL**	**GQ**	**FJ**
Relative efficiency		0.8	0.99	0.85	0.8	0.99	0.93	0.75	0.86	0.6	0.7	0.71
Input surplus	X_1	7.67	20.26	17.99	0	21.73	15.02	26.74	11.48	0.92	21.87	18.07
	X_2	0	0.07	0.06	0.05	0.21	0	0	0	0.02	0	0.03
	X_3	117.6	0	0	104.02	0	48.03	58.68	29.26	71.01	146.81	56.47
	X_4	0.2	0	1.7	0.6	0.25	2.68	1.7	0	3.37	0	0.85
	X_5	0.51	0	0.79	0.44	0.42	0.5	0.88	1.04	0.34	0.79	0.26
	X_6	0.5	0.18	1.22	0.47	0.28	1.65	0.09	0.76	0.75	0.17	0.29
	X_7	2.08	7.58	5.64	0.16	6.91	1.28	3.3	1.97	0	2.01	0
Output deficiency	Y_1	25.93	39.63	30.02	6.95	4.83	15.95	89.51	12.77	35.32	24.93	20.76
	Y_2	4.46	3.14	3.87	2.76	1.74	1.38	3.16	3.47	2.12	2.4	3.9
	Y_3	2.64	1.39	2.97	1.34	0.98	1.12	2.35	2.91	2.59	2.44	1.87
	Y_4	14.64	7.88	12.05	3.42	12.86	18.41	15.24	19.71	17.76	6.08	8.29
	Y_5	3.72	4.34	4.61	1.24	0	2.62	0	0	0	5	2.18
	Y_6	274.58	216.4	149.62	163.61	221.25	0	238.37	250.73	215.14	338.16	93.11
	Y_7	0	0	0	0	0	1.28	2.4	2.61	1.87	0	0
	Y_8	16.36	19.32	10.93	11.25	10.71	11.74	22.26	10.8	14.29	29	12.17
	Y_9	34,614	18,920	16,904	16,885	8379	33,741	38,325	40,435	10,596	20,576	15,148

Input indexes analysis: 10 refining enterprises are characterized by an overly high asset–liability ratio and thus high operational risks; only 6 refining enterprises are demonstrated to have high energy consumption per unit of output, which indicates the efforts by most enterprises; 8 enterprises have a high total cost per unit, which should be lowered by technological advancement; 8 enterprises should be criticized due to their excessive waste solid emission and 10 due to wastewater emission; 11 enterprises actually have a variable degree of redundancy of waste gas emission amount, which suggests more efforts to reduce the emission of "three wastes"; and 9 enterprises have high turnover rates, indicating a need to improve benefits and thus enhance the staff employment stability.

Output indexes analysis: 11 enterprises are found to have a low return on assets and asset turnover, which implies unsatisfactory economic benefits; 11 enterprises have a low proportion of investment in science and technology and the R&A personnel, which should be enhanced; besides 4 enterprises whose comprehensive commodity rates are 0, the other enterprises have relative larger comprehensive commodity rates, indicating good control effects; 10 enterprises should be criticized due to their generally large deficit in the environmental protection investment per 10 thousand yuan of output value, which indicates the existing large gap between the deserved and actual investment amount; only 4 enterprises have disposal rates larger than 0, which means relatively good "three wastes" disposal effects; and 11 enterprises have relatively low social contribution and income per capita, which should be improved by management optimization.

According to the principle of projection, DMU values indicating low efficiency are adjusted. We use the adjustment of the QL, ZH, and FJ companies as the case study. The reason why we select these three companies are explained as follows: Firstly, the purpose of selecting scaly and technically inefficient enterprises is to explore factors affecting sustainable development, and thus propose improvement countermeasures aiming to set examples for other companies as a reference. Regarding the three selected companies, QL is characterized by the lowest DMU value with largest improvement space, and thus it was selected. In addition to four companies with strong sustainability, DMU values of the YS and DL companies are very close to 1, but their limited improvement space is lower than that of the ZH company. As for the FJ company, it was randomly selected among the left ones (other alternatives are an option). The reason for selecting them for the empirical case study is to provide enhancement information, as the factors restricting their sustainable development vary with their actual situation. The adjusted values and the adjustment ratio are shown in Table 5.

Table 5. Target and adjusted values of input and output indexes of the QL, ZH, and FJ companies.

	QL Relative Efficiency = 0.60			ZH Relative Efficiency = 0.93			FJ Relative Efficiency = 0.70		
	Original Value	Optimized Target Value	Adjustment Ratio	Original Value	Optimized Target Value	Adjustment Ratio	Original Value	Optimized Target Value	Adjustment Ratio
X_1	13.17	1.69	−87.15%	22.83	1.10	−95.16%	23.33	1.46	−93.74%
X_2	0.42	0.42	0.00%	0.48	0.27	−42.92%	0.36	0.36	0.00%
X_3	166.67	137.41	−17.55%	89.65	89.65	0.00%	265.34	118.53	−55.33%
X_4	0.00	0.00	0.00%	0.25	0.00	−100%	0.00	0.00	0.00%
X_5	1.14	0.10	−91.37%	0.49	0.06	−86.78%	0.87	0.09	−90.23%
X_6	0.86	0.10	−88.14%	0.35	0.07	−80.98%	0.26	0.09	−66.22%
X_7	8.90	6.93	−22.09%	11.43	4.52	−60.42%	7.99	5.98	−25.14%
Y_1	−9.15	−2.40	73.78%	−5.97	−1.57	73.78%	−19.05	−2.07	89.14%
Y_2	2.87	8.22	186.77%	3.38	5.36	58.54%	3.31	7.09	114.16%
Y_3	1.19	4.88	310.08%	2.06	3.18	54.55%	1.25	4.21	236.75%
Y_4	15.37	35.19	128.95%	15.50	29.48	90.19%	23.21	38.98	67.93%
Y_5	95.10	95.10	0.00%	95.94	95.94	0.00%	92.41	95.98	3.86%
Y_6	89.15	398.51	347.01%	36.14	259.99	619.39%	3.94	343.74	999.90%
Y_7	97.55	100.00	2.51%	100.00	100.00	0.00%	100.00	100.00	0.00%
Y_8	14.19	34.32	141.89%	10.90	22.39	105.45%	0.43	29.61	999.90%
Y_9	47,099.45	98,507.69	109.15%	82,566.34	96,889.00	17.35%	75,865.25	98,099.64	29.31%

The input indexes of the QL company, except the "three wastes" disposal rate and comprehensive commodity rate, should be dramatically adjusted, especially for the investment in science and technology and for that in environmental protection, which should be 3.1 times and 3.47 times higher, respectively. Meanwhile, large adjustments should also be implemented to the asset–liability ratio and the waste water/gas emissions per unit of output, whose adjustment ratios are around 90%. More efforts should be paid by the QL company to improve the economic benefit, scientific research investment, environmental protection investment, "three wastes" emission control, social contribution, and worker protection. As for the ZH company, its environmental protection investment per 10 thousand yuan of output is low, while the "three wastes" emission is high, which have to be enhanced by 6.19 times and lowered by 80%, respectively. Meanwhile, the asset–liability ratio, the return on assets, and the asset turnover should also be adjusted by 50–90%. In addition, the ZH company, in the refining and petrochemical industry with remarkable scale benefits, should actively adjust its profit rate and main operational revenue. There is also room for improvement in the investment intensity in science and technology, R&A personnel, comprehensive energy consumption per unit of output, the employee turnover rate, and the social contribution rate. When it comes to the FJ company, adjustment should be made in both input and output indexes. Output indexes, in addition to the comprehensive energy consumption and solid waste emissions per unit of output, need to be greatly adjusted, among which environmental protection investment per 10 thousand yuan of output and the social contribution rate should be modified by more than 10 times. Meanwhile, the input indexes should be adjusted to different degrees besides the comprehensive energy consumption per unit of output and the solid waste emissions per unit of output. Therefore, systematic and comprehensive measures should be taken to improve the sustainability of the FJ company.

5. Conclusions and Policy Recommendations

5.1. Conclusions

With more stringent regulation for environmental protection, refining enterprises are confronted with the challenge of balancing economic profit gains and environmental friendly development. Only sustainable development can help refineries escape the dilemma. Accordingly, this paper carries out a DEA model for the sustainability evaluation of refining enterprises, which points out restriction factors for further optimization. Furthermore, 15 selected refineries are taken as examples to prove the power of this model and help achieve sustainable development. The conclusions of this study are as follows:

(1) The sustainability of refining enterprises is divided into three categories: economic, ecological, and social sustainability. Each category is identified by specific indexes. Based on the sustainability analysis results and specific features of refineries, this paper establishes a sustainability evaluation index system for refining enterprises, which contains 17 representative indexes for refineries' sustainability development. Furthermore, a DEA-based model is proposed to evaluate the sustainable level of refineries, which can provide improvement measures rather than exclusively evaluate sustainability. (2) Taking 15 selected refining enterprises with similar business scales as examples, we evaluated the sustainable level by employing the DEA model. The results revealed the sustainability performance of each enterprise and discussed the main factors affecting the sustainability in the case of three enterprises with low DMU values. It is suggested that adjustment should be implemented and comprehensive measures should be taken on the basis of projection analyses in order to improve sustainability.

5.2. Policy Recommendations

According to the DEA-based evaluation results of the sustainability of oil refining enterprises, suggestions are proposed as follows:

(1) Active measures should be taken to reduce total cost per unit. This can be achieved by separating each cost or expense, and corresponding financial indexes can then be established to

formulate a suitable index system. The transparency of individual costs should be improved, and corresponding control and supervision is critical. Cost assessment should be completed on a regular basis, and an evaluation mechanism linked to performance should be designed.

(2) Investment in science and technology should be enhanced to maintain continuous innovation. Critical technologies should be mastered before they become dominant in the future, and so should the relevant intellectual property rights. The gradual demonstration and modification should be highlighted, and special attention must be paid to the popularization and commercial application of those technologies.

(3) Energy conservation and emission reduction should be implemented to achieve clean production. From the energy conservation prospect, technology and operation management levels should be enhanced, which can be implemented by reducing heat loss through technological innovation based on designed value. From an emission reduction perspective, emphasis should be placed on the source of pollutants, which should be reduced from the very beginning by process optimization. Meanwhile, the recycling of "three wastes" and the reuse of wastewater is emergent.

(4) Social contribution rates and employee benefits should increase. While continuously improving social contributions and social accumulation rates, refining enterprises should also be actively involved in public welfare and shoulder more social responsibilities.

Acknowledgments: This paper is financially supported by the National Natural Science Foundation of China (No. 71273277) and the Key Projects of the Philosophy and Social Science Researches of Ministry of Education of China (No. 11JZD048). In addition, the authors thank the editors and the anonymous reviewers of this manuscript for their elaborate work.

Author Contributions: All of the authors have co-operated in the preparation of this work. Hui Li wrote the paper. Renjin Sun made contributions to the design of the article. Kangyin Dong and Jintao Yu collected and analyzed the data. A final review, including final manuscript revisions, was performed by Jinhong Xu.

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

References

1. Luan, W.; Lu, L.; Li, X.; Ma, C. Weight Determination of Sustainable Development Indicators Using a Global Sensitivity Analysis Method. *Sustainability* **2017**, *9*, 303. [CrossRef]
2. Abdul-Manan, A.F.N.; Arfaj, A.; Babiker, H. Oil refining in a CO_2 constrained world: Effects of carbon pricing on refineries globally. *Energy* **2017**, *121*, 264–275. [CrossRef]
3. Walls, W.D. Petroleum refining industry in China. *Energy Policy* **2010**, *38*, 2110–2115. [CrossRef]
4. Xu, H.F. Review and trend of world oil refining industry in 2014. *Int. J. Pet. Econ.* **2015**, *23*, 47–53. (In Chinese)
5. Hua, Y.W. Petrochemical industry make green development action in 2020 by reducing the energy consumption and carbon dioxide emissions. *Chin. J. Pet. Chem. Eng.* **2016**, *2016*, 78. (In Chinese)
6. Dong, K.; Sun, R.; Li, H.; Zheng, S.; Yuan, B.; Chung, K. Weaker demand outlook, heightened regulations create uncertainty for Chinese refiners. *Oil Gas J.* **2016**, *114*, 63–67.
7. Bandyopadhyay, M.; Dutta, A.; Dikshit, A.K.; Ray, S. Environmental impact assessment and its minimization in a refinery for sustainable development. *Interdiscip. Environ. Rev.* **2001**, *3*, 156–167. [CrossRef]
8. Büyüközkan, G.; Karabulut, Y. Energy project performance evaluation with sustainability perspective. *Energy* **2017**, *119*, 549–560. [CrossRef]
9. Li, H.; Sun, R.; Lee, W.J.; Lee, W.; Dong, K.; Guo, R. Assessing Risk in Chinese Shale Gas Investments Abroad: Modelling and Policy Recommendations. *Sustainability* **2016**, *8*, 708. [CrossRef]
10. Anvaripour, B.; Sa'idi, E.; Nabhani, N.; Jaderi, F. Risk Analysis of Crude Distillation Unit's assets in Abadan Oil Refinery Using Risk Based Maintenance. *TJEAS J.* **2013**, *3*, 1888–1892.
11. Calabrese, A.; Costa, R.; Levialdi, N.; Menichini, T. A fuzzy Analytic Hierarchy Process method to support materiality assessment in sustainability reporting. *J. Clean. Prod.* **2016**, *121*, 248–264. [CrossRef]
12. Arce, M.E.; Saavedra, Á.; Míguez, J.L.; Granada, E. The use of grey-based methods in multi-criteria decision analysis for the evaluation of sustainable energy systems: A review. *Renew. Sustain. Energy Rev.* **2015**, *47*, 924–932. [CrossRef]

13. Dong, X.; Guo, J.; Höök, M.; Pi, G. Sustainability assessment of the natural gas industry in China using principal component analysis. *Sustainability* **2015**, *7*, 6102–6118. [CrossRef]
14. Chen, X.; Gong, Z. DEA Efficiency of Energy Consumption in China's Manufacturing Sectors with Environmental Regulation Policy Constraints. *Sustainability* **2017**, *9*, 210. [CrossRef]
15. Li, J.Q.; Zhang, Z.X.; Li, Y.C.; Li, Y. Comprehensive appraisement analysis on sustainable development of oil-refining enterprise. *J. Univ. Pet.* **2003**, *27*, 121–124. (In Chinese).
16. Lv, H.Y.; Wang, Y.Q. Sustainability evaluation system of refineries. *Bord. Econ. Cult.* **2007**, *2017*, 38–39. (In Chinese)
17. Dong, K.; Sun, R.; Jiang, H.; Li, H. Integrated Evaluation of Circular Economy Method for Chinese Petroleum Refining Industry. *Oxid. Commun.* **2017**, *39*, 3998–4013.
18. Sexton, T.R. The methodology of data envelopment analysis. *New Dir. Eval.* **1986**, *1986*, 7–29. [CrossRef]
19. Mardani, A.; Zavadskas, E.K.; Streimikiene, D.; Jusoh, A.; Khoshnoudi, M. A comprehensive review of data envelopment analysis (DEA) approach in energy efficiency. *Renew. Sustain. Energy Rev.* **2016**, *70*, 1298–1322. [CrossRef]
20. Norman, M.; Stoker, B. *Data Envelopment Analysis: The Assessment of Performance*; John Wiley & Sons: Hoboken, NJ, USA, 1991.
21. Singh, R.K.; Murty, H.R.; Gupta, S.K.; Dikshit, A.K. An overview of sustainability assessment methodologies. *Ecol. Indic.* **2012**, *15*, 281–299. [CrossRef]
22. Malana, N.M.; Malano, H.M. Benchmarking productive efficiency of selected wheat areas in Pakistan and India using data envelopment analysis. *Irrig. Drain.* **2006**, *55*, 383–394. [CrossRef]
23. Rossi, P.H.; Lipsey, M.W.; Freeman, H.E. *Evaluation: A Systematic Approach*; Sage Publications: Thousand Oaks, CA, USA, 2003.
24. Yuan, Q.M.; Qiu, J. An Evaluation Research on Tianjin Marine Economy Sustainable Development via PCA and DEA. In *Applied Mechanics and Materials*; Trans Tech Publications: Zurich, Switzerland, 2014; Volume 448, pp. 4065–4070.
25. Cooper, W.W.; Seiford, L.M.; Zhu, J. Data envelopment analysis. In *Handbook on Data Envelopment Analysis*; Springer: New York, NY, USA, 2004; pp. 1–39.
26. Johnstone, N.; Managi, S.; Rodríguez, M.C.; Haščič, I.; Fujii, H.; Souchier, M. Environmental policy design, innovation and efficiency gains in electricity generation. *Energy Econ.* **2017**, *63*, 106–115. [CrossRef]
27. Yagi, M.; Fujii, H.; Hoang, V.; Managi, S. Environmental efficiency of energy, materials, and emissions. *J. Environ. Manag.* **2015**, *161*, 206–218. [CrossRef] [PubMed]
28. Fujii, H.; Managi, S. Optimal production resource reallocation for CO_2 emissions reduction in manufacturing sectors. *Glob. Environ. Chang.* **2015**, *35*, 505–513. [CrossRef]
29. Basiron, Y.; Weng, C.K. The oil palm and its sustainability. *J. Oil Palm Res.* **2004**, *16*, 1–10.
30. Venetoulis, J.; Talberth, J. Refining the ecological footprint. *Environ. Dev. Sustain.* **2008**, *10*, 441–469. [CrossRef]
31. Goodland, R. The concept of environmental sustainability. *Annu. Rev. Ecol. Syst.* **1995**, *26*, 1–24. [CrossRef]
32. Siche, J.R.; Agostinho, F.; Ortega, E.; Romeiro, A. Sustainability of nations by indices: Comparative study between environmental sustainability index, ecological footprint and the emergy performance indices. *Ecol. Econ.* **2008**, *66*, 628–637. [CrossRef]
33. Perrini, F.; Tencati, A. Sustainability and stakeholder management: The need for new corporate performance evaluation and reporting systems. *Bus. Strategy Environ.* **2006**, *15*, 296–308. [CrossRef]
34. Zhong, W.; Yuan, W.; Li, S.X.; Huangm, Z. The performance evaluation of regional R&D investments in China: An application of DEA based on the first official China economic census data. *Omega* **2011**, *39*, 447–455.
35. Ness, B.; Urbel-Piirsalu, E.; Anderberg, S.; Olsson, L. Categorising tools for sustainability assessment. *Ecol. Econ.* **2007**, *60*, 498–508. [CrossRef]
36. Khanna, N. Measuring environmental quality: An index of pollution. *Ecol. Econ.* **2000**, *35*, 191–202. [CrossRef]
37. Zhu, Q.; Wu, J.; Li, X.; Xiong, B. China's regional natural resource allocation and utilization: A DEA-based approach in a big data environment. *J. Clean. Prod.* **2017**, *142*, 809–818. [CrossRef]
38. Labuschagne, C.; Brent, A.C.; Van Erck, R.P.G. Assessing the sustainability performances of industries. *J. Clean. Prod.* **2005**, *13*, 373–385. [CrossRef]

39. Šaparauskas, J.; Turskis, Z. Evaluation of construction sustainability by multiple criteria methods. *Technol. Econ. Dev. Econ.* **2006**, *12*, 321–326.
40. Strezov, V.; Evans, A.; Evans, T.J. Assessment of the Economic, Social and Environmental Dimensions of the Indicators for Sustainable Development. *Sustain. Dev.* **2016**. [CrossRef]
41. Vasconcelos, D.; Melo, M.B.; Souto, M.S.M.; Caldas, A.; Muniz, D. Good management practices of the waste and of the health and the safety conditions in the constructive process: Sustainability, social responsibility and ethical business activity. In *Occupational Safety and Hygiene IV*; CRC Press: New York, NY, USA, 2016; p. 133.
42. Charnes, A.; Cooper, W.W.; Rhodes, E. Measuring the efficiency of decision making units. *Eur. J. Oper. Res.* **1978**, *2*, 429–444. [CrossRef]
43. Zhou, H.; Hu, H. Sustainability evaluation of railways in China using a two-stage network DEA model with undesirable outputs and shared resources. *Sustainability* **2017**, *9*, 150. [CrossRef]
44. Chen, L.; Jia, G. Environmental efficiency analysis of China's regional industry: A data envelopment analysis (DEA) based approach. *J. Clean. Prod.* **2017**, *142*, 846–853. [CrossRef]
45. Afsharian, M.; Afsharian, M.; Ahn, H.; Neumann, L. Generalized DEA: An approach for supporting input/output factor determination in DEA. *Benchmarking Int. J.* **2016**, *23*, 1892–1909. [CrossRef]
46. Lovell, C.A.K.; Rouse, A.P.B. Equivalent standard DEA models to provide super-efficiency scores. *J. Oper. Res. Soc.* **2003**, *54*, 101–108. [CrossRef]
47. Golany, B.; Roll, Y. An application procedure for DEA. *Omega* **1989**, *17*, 237–250. [CrossRef]
48. Parkan, C.; Wu, M. Decision-making and performance measurement models with applications to robot selection. *Comput. Ind. Eng.* **1999**, *36*, 503–523. [CrossRef]