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Energy and environment efficiency analysis based on an improved environment DEA cross-model: Case study of complex chemical processes

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HIGHLIGHTS

- An improved environment DEA cross-model method is proposed.
- Energy and environment efficiency analysis framework of complex chemical processes is obtained.
- This proposed method is efficient in energy-saving and emission reduction of complex chemical processes.

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ABSTRACT

The complex chemical process is a high pollution and high energy consumption industrial process. Therefore, it is very important to analyze and evaluate the energy and environment efficiency of the complex chemical process. Data Envelopment Analysis (DEA) is used to evaluate the relative effectiveness of decision-making units (DMUs). However, the traditional DEA method usually cannot genuinely distinguish the effective and inefficient DMU due to its extreme or unreasonable weight distribution of input and output variables. Therefore, this paper proposes an energy and environment efficiency analysis method based on an improved environment DEA cross-model (DEACM) method. The inputs of the complex chemical process are divided into energy and non-energy inputs. Meanwhile, the outputs are divided into desirable and undesirable outputs. And then the energy and environment performance index (EEPI) based on the cross evaluation is used to represent the overall performance of each DMU. Moreover, the improvement direction of energy-saving and carbon emission reduction of each inefficiency DMU is quantitatively obtained based on the self-evaluation model of the improved environment DEACM. The results show that the improved environment DEACM method has a better effective discrimination than the original DEA method by analyzing the energy and environment efficiency of the ethylene production process in complex chemical processes, and it can obtain the potential of energy-saving and carbon emission reduction of ethylene plants, especially the improvement direction of inefficient DMUs to improve energy efficiency and reduce carbon emission.

1. Introduction

The main reason for global warming caused by human activities is the widespread use of fossil fuels (such as coal and oil) in the last decades, and it has emitted a large number of greenhouse gases into the atmosphere. In all greenhouse gases, carbon dioxide has the highest contribution rate, the longest survival period, and is the major factor that leads to climate change and global warming [1]. The petrochemical industry is an important industry related to national production and life. Meanwhile, the petrochemical industry is also a high pollution and high carbon emissions industry. Therefore, analyzing the energy and environment efficiency of the complex petrochemical industry is imperative.

In many environment efficiency evaluation methods, data envelopment analysis (DEA) method is widely used as a nonparametric programming method because of its very important practical significance and economic background, especially in the field of environment performance evaluation of enterprise micro-level [2]. The DEA method is an evaluation method based on the concept of relative efficiency and linear programming. The efficiency of the decision-making unit (DMU) in the DEA method is defined as the ratio of the weighted sum of the output variables to the weighted sum of the input variables. The efficiency index of the DMU is independent of the unit selection of inputs and outputs, so there is no necessary for dimensionless data processing of the DEA model. The DEA method also

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ruled out a lot of subjective factors because it does not need any weight assumption on the inputs and outputs. Therefore, the DEA method has a unique advantage in the efficiency evaluation of multiple inputs and multiple outputs. However, the traditional DEA method usually cannot genuinely distinguish the effective and inefficient DMUs due to its extreme or unreasonable weight distribution of input and output variables. In this paper, an improved environment DEA cross-model (DEACM) method is proposed. The inputs of a complex chemical process are divided into energy inputs and non-energy inputs. Meanwhile, the outputs are divided into desirable outputs and undesirable outputs. First, the improvement direction of energy utilization efficiency and carbon emission reduction of all inefficiency DMUs are obtained based on the self-evaluation model of the improved environment DEACM. Second, the energy and environment performance index (EEPI) based on the cross evaluation is used to represent the overall performance of each DMU. This proposed method has good efficiency discrimination ability, and it can also give the improvement direction of the inefficient DMU by quantitatively calculation. Moreover, the proposed method is applied to analyze the energy and environment efficiency of the complex ethylene production process. The results show that the proposed method can obtain the potential of energy-saving and emission reduction of ethylene plants, especially the improvement direction of all inefficient DMUs to improve energy utilization efficiency and reduce carbon emission.

The rest of the paper is organized as follows. Section 2 is the literature review of energy and environment efficiency analysis. Section 3 introduces the environment DEA cross-model to calculate the energy-saving and emission reduction potential. The improved environment DEACM is applied to analyze the energy and environment efficiency of the ethylene production process in the complex chemical process to prove the effectiveness of the proposed method in Section 4. Discussion and Conclusion are in s 5 and 6, respectively.

2. Literature review

The DEA method was first proposed by operational researchers Charnes, Cooper and Rhodes in 1978 [3]. Since then, the DEA method has been widely used to analyze the energy and environment efficiency. Xie et al. assessed the electric power industry in BRIC nations (China, India, Russia and Brazil) by adopting the environmental Malmquist index based on a SBM-DEA (slack based measure data envelopment analysis) model. And they found that fuel structure change and technological progress were the main driving forces to promote dynamic environmental efficiency [4]. Zhu et al. studied DEA combined with life-cycle environmental impacts of products for eco-efficiency evaluation to examine the eco-efficiencies of ten comparable pesticides. And they found out that the network DEA method can distinguish differences in the eco-efficiency of products at the different stages [5]. Cui et al. applied a virtual frontier DEA to evaluate transportation carbon efficiencies, and analyzed the cases from 15 countries during the period of 2003–2010. The results indicated that compared with the technology factor and management factor, the influencing degree of a structure factor is relatively small [6]. Wu et al. proposed a DEA-based approach to allocate China's national CO_2 emissions and energy intensity reduction targets over Chinese provincial industrial sectors. The results showed that the most effective allocation of the national reduction target requires most of the 30 regional industrial to reduce CO_2 emission and energy intensity, while a few can increase or maintain their 2010 levels [7]. Meng et al. conducted a comprehensive survey of empirical studies published in 2006–2015 on China's regional EE & CE assessment by using DEA-type models. The main features used in previous studies were identified, and then the methodological framework for deriving the EE & CE indicators as well as six widely used DEA models were introduced [8]. Li et al. applied a three-stage DEA model to measure the effects of government measures on green productivity growth and introduced an improved Malmquist–Luenberger productivity index to measure the green productivity growth of China's manufacturing sector during the 11-th Five-Year Period. They proved China's energy-saving policies and measures, such as closure and elimination of obsolete production capacity, and reduction of over-capacity is important for green development [9]. Hernández-Sancho et al. applied a non-radial DEA method to analyze energy efficiency indices for the sampling of wastewater treatment plants in Spain, and got the potential savings in economic terms and carbon emission to provide the guidance for the efficiency improvement [10]. Wei et al. investigated the energy efficiency of China's iron and steel sector from 1994 to 2003 by using Malmquist Index Decomposition [11]. Sueyoshi and Yang et al. studied the DEA window analysis for environment assessment in a dynamic time shift to evaluate the operational, environment and both-unified performance of coal-fired power plants [12–14]. In addition to the above applications, the DEA has been applied in the complex chemical process. Azadeh et al. used the fuzzy neural algorithm to evaluate the environment performance [15] and eco-efficiency [16] of large petrochemical plants, which is the first intelligent algorithm to evaluate the environment performance. Zhu et al. evaluated the energy efficiency by combining the DEA-CCR model and principal component analysis (PCA) to reduce the amount of data in petrochemical production processes [17]. In order to estimate the eco-efficiency of the industrial sector, Charmondusit provided a basic framework for the environment efficiency assessment of the Thai petrochemical plant and enable public participation in the discussion on branch developments and contributions to national trends [18]. Geng et al. used the Malmquist production index method based on DEACM and fuzzy DEACM to study the performance efficiency of Chinese ethylene plants [19]. Geng et al. proposes an efficiency analysis method based on FDEACM (fuzzy DEA cross-model) with fuzzy data. And the proposed method has better objectivity and resolving power for the decision-making [20]. However, the numbers of inputs and outputs indicators and the number of samples have a significant effect on the results of the DEA analysis [21,22]. Han et al. proposed a new energy analysis framework for the petrochemical industry process based on the DEA Comprehensive Interpretation Structure Model (ISM). Based on the partial correlation coefficient method, the ISM method was proposed to find out the main factors and basic causes of the energy consumption of ethylene production. This method can overcome the difficulties of different weight assessment and decision-making [23].

All the above methods for the environment efficiency evaluation do not achieve the purpose of emission reduction through energy-saving, and there is no quantitative analysis of energy-saving and emission reduction in these methods. In this paper, an energy and efficiency evaluation method based on an improved environment DEACM is proposed. This method classifies the inputs and outputs of complex chemical processes, estimates the carbon emissions, and combines the DEACM to obtain the efficiency of each plant. This proposed method can also use the relaxation coefficients and energy efficiencies to quantitatively calculate the energy-saving and emissionreduction potential, and provide the guidance for energy-saving and carbon emission reduction of ineffective DMUs.

3. The environment DEA cross-model

3.1. DEA cross-model

Each object of the DEA research problem is called a DMU. Assuming that there are n DMUs, and the data form of each DMU is:

$$DMU_i = [x_i \quad y_i] \quad i = 1,2,...,n$$

Wherein $x_i = [x_{1i},x_{2i},...,x_{mi}]^T, y_i = [y_{1i},y_{2i},...,y_{si}]^T$ are the m inputs and s outputs of i-th DMU, respectively.

Set $v = [v_1,v_2,...,v_m]^T, u = [u_1,u_2,...,u_s]^T$ are the weight vector of inputs and outputs, respectively. And then the efficiency value of DMU is $E_{ii} = \frac{y_i^T u}{x_i^T v}$.

The aim of CCR model of the DEA method is solving the optimal solution in Eq. (1).