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Energy efficiency analysis method based on fuzzy DEA cross-model for ethylene production systems in chemical industry

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A B S T R A C T

DEA (data envelopment analysis) has been widely used for the efficiency analysis of industrial production process. However, the conventional DEA model is difficult to analyze the pros and cons of the multi DMUs (decision-making units). The DEACM (DEA cross-model) can distinguish the pros and cons of the effective DMUs, but it is unable to take the effect of the uncertainty data into account. This paper proposes an efficiency analysis method based on FDEACM (fuzzy DEA cross-model) with Fuzzy Data. The proposed method has better objectivity and resolving power for the decision-making. First we obtain the minimum, the median and the maximum values of the multi-criteria ethylene energy consumption data by the data fuzzification. On the basis of the multi-criteria fuzzy data, the benchmark of the effective production situations and the improvement directions of the ineffective of the ethylene plants under different production data configurations are obtained by the FDEACM. The experimental result shows that the proposed method can improve the ethylene production conditions and guide the efficiency of energy utilization during ethylene production process.

1. Introduction

The development of chemical industry has become a main sign of industrialization of a country. The ethylene industry is one of the most important parts of the chemical industry. In 2012, China Petrochemical Corporation's ethylene production was 9475 kt/a, and the average fuel plus power consumption (standard oil) was 579.59 kg per ton of ethylene produced [1]. The ethylene production capacity of China National Petroleum Corporation was 5110 kt/a, and the fuel plus power consumption was 628.6 kg per ton of ethylene produced in 2012 [2]. Energy consumption costs of ethylene plants took up more than 50% of operating costs [3]. The energy efficiency of China ethylene industry is significantly lower than that of the advanced countries, so the study of energy efficiency analysis of ethylene plants is beneficial for both the environmental and the continued sustainable development of the Chinese economy.

Currently, the mean method and optimal index method to analyze energy efficiency are commonly used by enterprises [4]. However, the energy saving knowledge does not taken into account, so the two methods cannot give the energy efficiency value benchmarking of optimal factors and indices to guide the analysis of the actual energy efficiency state. Geng et al. proposed an energy efficiency analysis method of ethylene plants based on data fusion with better performance, but the method did not take the role of influential factors on energy consumption indicators into consideration [5,6]. These methods based on the DEA (data envelopment analysis) model and AHP (analytic hierarchy process) have been applied to the efficiency analysis of logistics, agriculture and other industries [7,8]. However, ethylene monthly data are the statistical data, which has the characteristics of multi-dimension, noise and uncertainty, resulting in the larger data error. It is difficult to evaluate accurately the energy efficiency production situation of each plant based on energy efficiency monthly data [9,10]. Frequently, the decision-making problems of ethylene plants are ill defined as their objectives and parameters are not precisely known. Therefore, this paper studies the energy efficiency analysis of China ethylene plants based on FDEACM (fuzzy DEA cross-model) with fuzzy data.

The rest of this paper has been organized as follows: Section 2 presents the research status of energy efficiency with DEA and

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fuzzy set. The fuzzy numbers and its operations are provided in Section 3. Section 4 presents the details of the FDEACM with fuzzy data. The energy efficiency analysis framework and process based on FDEACM in ethylene production industry are described in Section 5. Section 6 presents a case study about the energy efficiency analysis of ethylene production industry based on FDEACM. Finally, the conclusions are given in Section 7.

2. Literature review

In 1978, the DEA method was firstly proposed by the famous operational research experts A. Charnes, W.W. Cooper and E. Rhodes. They used the DEA to make 'production apartment', which had multiple inputs and multiple outputs, both 'sizeable effective' and 'technological effective'. Meanwhile, the highly relevant of input–output indicators would not affect the stability and reliability of the DEA [11]. Cook and Seiford provided some of the important areas of research about the DEA that have emerged over the past three decades [12]. The application of DEA turned out to be much satisfactory and effective [13], especially in the petrochemical industry. Sueyoshi and Yang et al. studied the DEA approach and the DEA window analysis for environmental assessment in a dynamic time shift to evaluate the operational, environmental and both-unified performance of coal-fired power plants, respectively [14–16]. Erturk and Turut-Aşık analyzed the performance of 38 Turkish natural gas distribution companies by using the DEA method to detect the important criteria affecting the efficient levels and find the common characteristics of the most inefficient firms, [17]. Liu et al. evaluate the power-generation efficiency of major thermal power plants in Taiwan during 2004–2006 by using the DEA approach [18]. Sueyoshi and Riccardi et al. incorporated the desirable and undesirable outputs for the performance evaluation of Japanese fossil fuel power generation and the world cement industry [19,20].

One limitation of the conventional DEA models is that they can only handle crisp input and output data. However, the observed values of the input and output data in real-world problems are sometimes imprecise or vague. Imprecise or vague data may be the result of unquantifiable, incomplete and nonobtainable information. Imprecise or vague data is often expressed with bounded intervals, ordinal (rank order) data or fuzzy numbers. In recent years, many researchers have formulated FDEA (fuzzy DEA) models to deal with situations where some of the input and output data are imprecise or vague. The aim of this paper is to study the fuzzy methods for dealing with the imprecise and ambiguous data in DEA.

Fuzzy set algebra developed by Zadeh is the formal body of theory that allows the treatment of imprecise and vague estimates in uncertain environments [21]. Meanwhile, the application of fuzzy set theory in real world decision-making problems has given very interesting results. Techniques of data fusion are integrated from a wide variety of disciplines including signal processing, pattern recognition, statistical estimation, artificial intelligence, fault diagnosis, control theory and engineering, etc [22–26]. Coppi et al. proposed an FKM (fuzzy *k*-means clustering) model for LR fuzzy data and a PKM (possibilistic *k*-means clustering) model for the same type of data. The results of two applications in car and student fuzzy data confirm the validity of both models [27]. Hullermeier briefly reviews some typical applications and highlights potential contributions that fuzzy set theory can make to machine learning, data mining, and related fields [28]. Chen et al. extend a fuzzy mining approach for handling time-series data to find linguistic association rules, and made some experiments to show the performance of the proposed mining algorithm [29]. Dubchak et al. proposed a fuzzy data processing method based on Mamdani's fuzzy inference method to reduce the number of operations during fuzzy data processing and improves its performance [30].

Since the original study by Sengupta there has been a continuous interest and increased development in FDEA literature [31,32]. Zhang et al. proposed a macro model and a micro model for the efficiency evaluation of data warehouses by applying DEA and FDEA models [33]. Chiang and Che proposed a new weight-restricted FDEA methodology for ranking new product development projects at an electronic company in Taiwan [34]. Kao and Lin explored a method for measuring the fuzzy efficiency of parallel production systems which involved a number of independent processes where the input/output data are fuzzy numbers [35]. Chen et al. incorporated FDEA technique into the SBM model to evaluate risk characteristics and estimate efficiencies in the banking sector [36]. Ghapanchi et al. employed FDEA to evaluate the performance of ERP (enterprise resource planning) packages [37]. Azadeh et al. used a triangular form of fuzzy inputs and outputs instead of the crisp data and proposed an FDEA model for calculating the efficient scores of the DMUs under uncertainty with application to the power generation sector [38]. Azadeh et al. explored an integrated approach for performance evaluation of health safety environment divisions, involving DEA and FDEA, to lessen the human error and the data imprecision [39]. Moreover, Azadeh et al. proposed an adaptive-network-based fuzzy inference system-FDEA algorithm for improving the long-term natural gas consumption forecasting and analysis [40].

The quantities of input and output indicators and the number of samples had an influence on the results of DEA and FDEA analysis [41,42]. The DEA model can lead to the situation that more than one-third of efficiency values are set to 1, so it means efficiency discrimination is poor. It also cannot obtain the sort of effective DMUs (decision-making units). Thus the DEA model can only distinguish the effective and ineffective units when analyzing enterprise production plant efficiency, but cannot give further evaluation and comparison of multi-effective DMUs. Moreover, in order to get the maximum efficiency evaluation index of each DMU, the weight allocation of input and output indicators is usually unreasonable [12]. Therefore the DEACM (DEA cross-model) is applied to analyze the energy efficiency status of the chemical industry.

In 1986, Sexton proposed the DEACM [43]. Chen used the DEA framework to compare cross-efficiency scores and the technical efficiency of the electricity distribution sector in Taiwan [44]. Wang and Chin introduced several kinds of the DEACM and its application [45]. Lu et al. study the DEACM to provide a theoretical basis for reference in grasping the actual level of thermal power units and charting the direction of improvement [46]. Yu et al. used the cross-efficiency DEA approach to identify the most efficient scenario and analyze the efficiency of each information-sharing scenario in supply chains [47]. The DEACM can distinguish the pros and cons of the effective DMUs, but it is unable to take the effect of the uncertainty data into account.

Considering the characteristics of the fuzzy set and the DEACM, this paper proposes an FDEACM based on fuzzy data. Firstly the monthly data are blurred to obtain the minimum, average and maximum values of ethylene production energy efficiency data. On the basis of the multi-criteria fuzzy fusion data, the corresponding energy efficiency situations of the ethylene plant under different production data configurations are obtained by the FDEACM. This approach is used to evaluate and analyze performance of petroleum chemical plants in the ethylene industry. It is reasonable to figure out efficiency indices of each plant and provide some advice about operation guidance for energy saving and performance improvement.