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Energy Efficiency Hierarchy Evaluation Based on Data Envelopment Analysis and its Application in a Petrochemical Process

A novel energy evaluation framework of petrochemical industrial processes based on a data envelopment analysis (DEA)-integrated analytic hierarchy process (AHP) model is proposed. An improved AHP method is brought up based on the differences of data themselves to build fusion matrices among energy consumption data. Then the fractional DEA model is solved by the linear programming method. The integrating evaluation method can overcome the usual shortcomings of the DEA model and is also able to reflect the effectiveness of decision-making units among different levels. A small number of such units are analyzed using the DEA model, and a multilevel integration of DEA efficiency values is disposed by the improved AHP method. The approach is firstly applied to the energy efficiency analysis of the ethylene production process in petrochemistry to improve energy consumption and efficiency.

Keywords: Analytic hierarchy process, Data envelopment, Energy efficiency, Ethylene production, Petrochemistry

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1 Introduction

The ethylene production level plays a key role in evaluating the industry development level of a country. In recent years, energy conservation and emission reduction has become one of the top topics focused on by all countries in the world. Energy saving is a priority in political laws to be written in national developing strategies in most countries. In 2008, according to statistics, the ethylene production capacity of Sinopec Corp. was 6359.4 kt and the ethylene plant energy consumption was 649.36 kg t^{-1} standard oil [1]. Similarly, those of Petro China Co. Ltd. were 2676 kt and 714 kg t^{-1} standard oil, respectively [2]. Their energy consumption is far greater than that of the advanced level abroad, which means that the ethylene industry in China has great improvement space for energy efficiency. The energy consumption cost amounted to more than half of the operation cost in ethylene production plants [3]. Thus, researches on energy efficiency evaluation can provide great economy benefits for petrochemical industries.

Currently, companies commonly use the mean method and optimal index method to analyze energy efficiency [4]. Since the energy efficiency value contains indicators and influencing factors, and various factors have different meanings to energy efficiency indicators, the mean method and optimal index method cannot introduce energy-saving knowledge into energy efficiency analysis and are not able to contribute to energy efficiency benchmarks of various factors and excellent indicators to guide the actual state of energy efficiency analysis. Geng et al. proposed an energy efficiency analysis method of ethylene plants based on data fusion with better performance. However, the approach did not consider the impact factors of energy consumption indicators [5, 6]. Additionally, researchers reduced the energy consumption of ethylene plants by optimizing the operation of cracking furnace or recovering the cold capacity from ethylene etc. [7, 8]. Kleemann et al. studied energy saving by optimal energy recovery in chemical process technology [9]. However, they did not consider the economic cost of reforming industry plants. Concerning disadvantages of the existing energy efficiency evaluation of the ethylene industry in China, this paper specifically proposes a method combining data envelopment analysis (DEA) with the improved analytic hierarchy process (AHP) to evaluate energy efficiency of ethylene production systems.

In 1978, the operational researchers Charnes, Cooper, and Rhodes firstly proposed the DEA method. They used it to make a 'production apartment', which had multiple inputs, especially multiple outputs, both 'sizeably effective' and 'technologically effective'. This application turned out to be satisfactory and effective [10]. AHP, which combines qualitative with quantitative analysis, is a hierarchical and multi-criterion analytic method [11–14]. It meets the requirement of multiple-solutions fusion

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under multiple criteria of the hierarchical mode of energy efficiency values. Khoshnevisan et al. studied this energy use efficiency in greenhouse cucumber production via the DEA approach [15]. Jablonsky analyzed two original models for ranking of efficient units in DEA, which are based on multiple criteria decision making techniques with goal programming and AHP [16]. Lin et al. evaluated the economic performance of local governments in China by combining AHP with DEA [17]. Houshyar et al. studied energy consumption efficiency for corn production utilizing DEA and AHP techniques [18]. Falsini et al. proposed a logistics provider evaluation and selection methodology based on AHP, DEA, and linear programming integration [19]. Our research group applied the DEA and AHP models to evaluate energy efficiency of ethylene production systems [20, 21].

DEA has been widely used for energy efficiency evaluation of enterprise plants. However, excessive decision-making units of the DEA model not only create too many "1" in the values of decision-making units' efficiency, but also lead to difficulties in evaluation and comparison of the different decision-making units.

First, DEA is utilized to analyze the efficiency value of different plants under the same technology based on the monthly data in a given year. At the same time, the model provides the energy efficiency of the ethylene production plant to find the improvement direction of ineffective decision-making units. Then, the monthly data of ethylene production plants under the same technology are weighted fused by the improved AHP. Finally, the annual data of ethylene industry and energy efficiency data from different technologies are used to evaluate their relative effectiveness by DEA. This approach is applied to determine layer by layer the comprehensive energy consumption of the ethylene industry and offer demonstration and reference to establish scientific benchmarks. Further, it can be employed to evaluate and analyze reasonably the energy efficiency in petroleum chemical plants, offering operation guidance for energy saving.

2 DEA-Integrated AHP

The DEA method is a classic efficiency or performance evaluation method. Too much decision-making units of DEA will result in a higher proportion of effective decision-making units in the evaluation of results and cannot distinguish the pros and cons. However, the AHP fusion algorithm can fuse similar multi-criterion data in a layered way and improves the accuracy of the DEA model depicting the multi-criteria decision making units' production frontier line.

2.1 DEA with Linear Programming Method

The first model of DEA analysis is named CCR model. In 1986, Charnes et al. established the new DEA model C^2WH, which reflects the preferences of decision makers as well as the evaluation of the technology and scale, briefly as follows:

There are n supposed departments or units, namely decision making units (DMUs). Each DMU has m inputs and s outputs, in which x_j[1)] $= (x_{1j}, x_{2j},\ldots; x_{mj})^T > 0$, $y_j = (y_{1j}, y_{2j},\ldots, y_{mj})^T > 0$, x_{ij} equals to inputs to i^{th} input of DMU$_{-j}$, y_{ij} equals to outputs to r^{th} output of DMU$_{-j}$ ($j = 1, 2,\ldots, n$; $i = 1, 2,\ldots, m$; $r = 1, 2,\ldots, s$). DMU$_{-j0}$ has corresponding input and output data of $x_0 = x_{j0}$, $y_0 = y_{j0}$ ($1 \le j0 \le n$). The DEA model C^2WH for evaluating DMU$_{-j0}$ is presented in Eq. (4) as fractional programming.

$$\begin{cases} \max \mu^{\mathrm{T}}\, y_0 \\ v^{\mathrm{T}}\, x_j - u^{\mathrm{T}}\, y_j \in K.j = 1, 2, \cdots, n \\ u \in U - \{0\} \\ v \in V - \{0\} \end{cases} \tag{1}$$

wherein $v = (v_1, v_2,\ldots, v_m)^T$ and $v = (u_1, u_2,\ldots, u_s)^T$, respectively, represent weight coefficients of m inputs and s outputs, $U \subset R^m$, $V \subset R^s$, $K \subset R^n$, and $\ln tV \neq \emptyset$, $\ln tU \neq \emptyset$. The C^2WH model transformation formula for fractional programming, proposed by Charnes and Cooper in 1962, for the DEA model is here applied:

$$\begin{cases} \max u^{\mathrm{T}}\, y_0 = v^0, \\ v^{\mathrm{T}}\, x_j - u^{\mathrm{T}}\, y_j \ge 0, j = 1, 2, \cdots, n, \\ u^{\mathrm{T}}\, x_0 = 1, \\ u \ge 0, v \ge 0 \end{cases} \tag{2}$$

The fractional model C^2WH could be transformed into equivalent linear programming as follows:

$$\begin{cases} \min \theta, \\ \sum_{j=1}^{n} x_j \lambda_j \le \theta x_0, \\ \sum_{j=1}^{n} y_j \lambda_j \ge y_0, \\ \lambda_j \ge 0, j = 1, 2, \cdots, n, \theta \in \mathbf{E}^1. \end{cases} \tag{3}$$

in which $\mathbf{E}^1$ is a unit vector. The equation form of the dual model in Eq. (3) with slack variables and the non-Archimedean infinitesimal ε is applied here, which is the input-oriented line of the DEA model, to get Eq. (4):

$$\begin{cases} \min[\theta - \varepsilon(e_1^{\mathrm{T}}\, s^- + e_2^{\mathrm{T}}\, s^+)], \\ \sum_{i=1}^{n} \lambda_i\, x_{ji} + s^- = \theta x_{jA}, j = 1, 2, \ldots, m \\ \sum_{i=1}^{n} \lambda_i\, y_{ri} - s^+ = y_{rA}, r = 1, 2, \ldots, s \\ \lambda_i \ge 0, i = 1, 2, \ldots, n, \\ s^- \ge 0, s^+ \ge 0, A = 1, 2, \ldots, n \end{cases} \tag{4}$$

where e is a non-Archimedean value designed to enforce strict positivity on the variables; ε is an abstract number, which is less than any positive number and greater than 0. The specific value of ε is set as small as possible to ensure ε close to the infinitesimal. Also, in order to ensure the convergence of computing, the specific value of ε is set as large as possible. In this paper, in order to separate efficient and weakly efficient DMUs, ε is set to 10^{-6} [22–24], and s_t^- and s_t^+ are the slack variables,

1) List of symbols at the end of the paper.

$s_t^- = (s_t^{1-}, s_t^{2-}, ..., s_t^{m-})^T$, $s_t^+ = (s_t^{1+}, s_t^{2+}, ..., s_t^{r+})^T$ are the redundancy amounts of m input items and the shortfall of s output items, respectively. $e_1^T = (1, 1, ..., 1) \in R^m$, $e_2^T = (1, 1, ..., 1)^T \in R^s$, θ is the optimum value of DMU$_{-j0}$, which stands for the efficiency of degree of inputs relative to outputs. Thus, if $\theta < 1$, DMU$_{-j0}$ is DEA-ineffective; if $\theta = 1$, DMU$_{-j0}$ is effective or weakly effective according to the establishment or not of the two constrained inequalities. All DMUs that are DEA-effective constitute the production-effective frontier. Moreover, the further the value of θ is from the production frontier, the lower is the relative efficiency [25].

2.2 Improved AHP Fusion Model

Zhang et al. analyzed the E-commerce security by AHP [26]. A decision network model for supplier selection based on AHP was designed in [27]. Jiang et al. evaluated the real estate's risk based on the AHP and simulation [28]. Some researchers studied the improved AHP fusion model [29–31], but such models are based on the comparison matrix, subjective judgment, and this objectivity is poor. So, here an improved AHP fusion model is proposed based on the data differences, which can establish the parity matrix and are objective.

Definition 1: supposing that the correlation function of the j^{th} parameter in a plant is $k_{ij}(x)$ from the i^{th} sampling, then the correlation function is called standard correlation function; $x_j(1)$, $x_j(2)$, $x_j(3)$, and $x_j(4)$ are nodes of $k_{ij}(x)$.

$$k_{ij}(x) = \begin{cases} 0 & x \notin [x_j(1), x_j(4)] \\ \frac{x_{ij} - x_j(1)}{x_j(2) - x_j(1)} & x \in [x_j(1), x_j(2)] \\ 1 & x \in [x_j(2), x_j(3)] \\ \frac{x_j(4) - x_{ij}}{x_j(4) - x_j(3)} & x \in [x_j(3), x_j(4)] \end{cases} \tag{5}$$
$$i = 1, 2, \cdots n; j = 1, 2, \cdots m$$

If the second and third nodes $x_j(2)$ and $x_j(2)$ of the standard correlation function are coincided, then $k_{ij}(x)$ is the underside correlation function [32, 33].

$$k_{ij}(x) = \begin{cases} 0 & x \notin [x_j(1), x_j(4)] \\ \frac{x_{ij} - x_j(1)}{x_j(2) - x_j(1)} & x \in [x_j(1), x_j(2)] \\ \frac{x_j(4) - x_{ij}}{x_j(4) - x_j(2)} & x \in [x_j(2), x_j(4)] \end{cases} \tag{6}$$
$$i = 1, 2, \cdots n; j = 1, 2, \cdots m$$

Supposing that energy efficiency timing data after preprocessing are $X = [X(1)\ X(2)\ \ldots\ X(n)]^T$, $X(i)$ $(i = 1, 2, \ldots, n)$ is the energy efficiency value of ethylene plants at the moment of $t = i$. The underside correlation function is adopted here, and $x_j(2)$ $(j = 1, 2, \ldots, m)$ is the average value. The information matrix $K_{n \times m}$ is defined as follows:

$$K_{n\times m} = \begin{bmatrix} k_{11} & k_{12} & \cdots & k_{1m} \\ k_{21} & k_{22} & \cdots & k_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ k_{n1} & k_{n2} & \cdots & k_{nm} \end{bmatrix} \tag{7}$$

After centralizing and normalizing, information data are transformed into $k'_{ij} = (k_{ij} - \overline{k_j})/S_j$, i = 1, 2,…, n; j = 1, 2,…, m, whereas $\overline{k_j} = \frac{1}{n}\sum_{i=1}^{n} k_{ij}$ and $S_j = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(k_{ij} - \overline{k_j})}$. Then, all negative values are shifted to zero (negative zero plus a positive decimal value φ, such as $\varphi = 0.000001$), i.e., $r_{ij} = k'_{ij} - t_j + \varphi$, where $t_j = \min(k'_{ij}) < 0$. Therefore, a positive matrix $R_{n\times mj}$ is derived:

$$R^j{}_{n\times m} = R_{n\times m} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \tag{8}$$

Then, an n-dimensional matrix is derived by $COR_{n\times n}$:

$$COR = RR^T = \begin{bmatrix} o_{11} & o_{12} & \cdots & o_{1n} \\ o_{21} & o_{22} & \cdots & o_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ o_{n1} & o_{n2} & \cdots & o_{nn} \end{bmatrix} \tag{9}$$

For the n-order symmetric matrix COR, its eigenvector $\mathbf{W} = (w_1, w_2, \ldots, w_n)^T$ is derived through the geometric mean method as follows: $w_i = o_i/o$ $(i = 1, 2, \ldots, n)$, in which $o_i = (\prod_{j=1}^{n} o_{ij})^{\frac{1}{n}}$ and $o = \sum_{i=1}^{n} o_i$.

Making use of the vector $\mathbf{W}$ to integrate schemes, the integration data X_{ref} of energy efficiency values of ethylene production plants are obtained:

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \cdots \\ y_m \end{bmatrix}^T = X^T W$$
$$= \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix}^T \begin{bmatrix} w_1 \\ w_2 \\ \cdots \\ w_n \end{bmatrix} \tag{10}$$

3 Energy Efficiency Analysis Framework and Process Based on DEA Integrating AHP in Ethylene Production Industry

There are about seven common process technologies in Chinese ethylene product industries [34]. Herein, the Lummus order separation technology is taken as an example to illustrate the effectiveness of the proposed method.

The ethylene production can be divided into two parts: cracking and separation. When a cracking furnace is running, a large amount of fuels are needed to provide heat to the tube cracking reactions, and a transfer line exchanger (TLE) produces a great amount of steam by recovering the waste heat. In order to make the raw material hydrocarbon finish the optimal cleavage reactions in a short time and at the same time to reduce coke, steam should be injected when the hydrocarbon is fed into the cracking furnace.

The separation section mainly contains three parts: rapid cooling, compression, and a separation part. The main energy consumption is related to the power of the compressor, heat separation such as the consumption of steam, and cooling energy consumption of the compressor and the cold box. A typical framework of a sequential separation process is illustrated in Fig. 1.

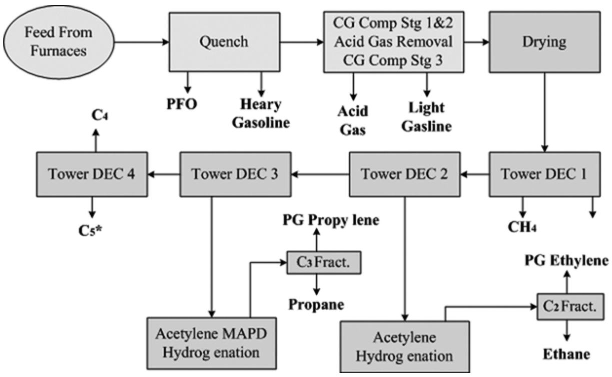

Figure 1. Typical framework of a sequential separation process.

3.1 Energy Boundary of Ethylene Production System

Different ethylene production plants may be quite different in the division of the energy utilization boundary. For ethylene plants, the production efficiency is directly related to the main factors including feedstock, utilities, and products. In order to create an unanimous criterion of computing energy efficiency objectively, refer to the ethylene industrial standards (DB37/751-2007) and national standards for energy consumption (GB/T2589-2008) in China [35, 36]. The energy utilization boundary of an ethylene production system is described in [34].

The main energy types are involved in the ethylene utilization boundary as follows: water including recycle water, industrial water, and boiler water; power (electricity); steam including super-high-pressure steam, high-pressure steam, middle- and low-pressure steam; fuels including fuel gas, light oil, and heavy oil; N_2 and compressing air. Because of the lowest consumption of N_2 and compressing air among the energy types, these were not computed considering energy efficiencies of the ethylene production process. According to the statistics, the energy consumption fees make up more than 50 % of the total cost for the ethylene production process. Therefore, the consumption of feedstock and utilities mainly including fuel, steam, water, and electricity are taken as inputs of ethylene production, and the yields of the main products ethylene and propylene are taken as outputs [20, 21, 34].

3.2 Data Preprocessing

Ethylene production data has a complex nonlinear timing relationship and includes noise and abnormal data, etc. The dimension for variables of timing data is generally different, which makes values of variables incomparable [20]. At the same time, it can be concluded from the model above that efficiency of DEA is relative. The accuracy of analysis results is easily affected by multi-input and multi-output data of DMUs and their precision. Thus, a consistency test and normalized and uniform dimension disposal of units are applied to process the data. The following formula is for long-term data and will lead to erroneous judgment for short-term data [19]. Long-term data could be tested according to Grubbs criterion [37]: if $T \geq T(n,\alpha)$, then x_i is eliminated, n denotes the number of data, and α is the significant level.

$$T = \frac{|V|}{S} = \frac{|x_i - \overline{x}|}{S} \tag{11}$$

where $\overline{x}$ and S express the mean and variance, respectively, the value of $T(n,\alpha)$ refers to [34].

Based on characteristics of energy efficiency data of ethylene production plants, the general method to express its level is to convert measure units of energy consumption parameters of fuel, electricity, water, and steam into uniform GJ. This conversion is based on Tabs. 3.0.2 and 3.0.3 from the Energy Consumption Calculation Method of Petroleum Chemical Design (SH/T3110-2001) [38].

The general transformation method is by proportion. However, the described subjects of timing data need to be taken into account, too. For the same subject, different variables make various interactions, some of which are positive [34], while others are negative. The respective formulas are given in Eqs. (12) and (13).

$$x_{ij}^{'} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}} \tag{12}$$

$$x_{ij}^{'} = 1 - \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}} = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}} \tag{13}$$

in which $x_j^{\max} = \max\{x_{1j}, x_{2j}, \cdots, x_{tj}\}$, $x_j^{\min} = \min\{x_{1j}, x_{2j}, \cdots, x_{tj}\}$, $i = 1, 2, \ldots, t$; $j = 1, 2, \ldots, m$.

3.3 Analysis Process of the Ethylene Plant Efficiency

The process of ethylene production is considered as a multi-input and multi-output process. The abnormal and noise data made by the process could be rejected through a consistency test, normalized and uniform dimension disposal of units. After data disposal, the multi-input and multi-output data can be sorted more accurately and objectively. Then, the precision of energy efficiency evaluation of ethylene production plants improve significantly through DEA model and AHP analyses. These works are able to demonstrate the methods of disposing feed costs under various production technologies for different plants, the ways to improve production design and energy efficiency, and how to increase outputs. The energy efficiency analysis procedures of ethylene production plants based on DEA and AHP methods are as follows:

Step 1: Select the monthly data for different plants under the same technology in one year, and then carry on the consistency test, normalized and uniform dimension disposal of units according to Eqs. (11) – (13).

Step 2: Analyze the monthly data per year of ethylene production efficiency for different plants by DEA to get the monthly ethylene production efficiency values, i.e., the efficiency values of steam, fuel, water, and electricity, of different plants.

Step 3: The monthly ethylene production efficiency values of different plants are weighted by AHP fusion to get the monthly benchmark efficiency values of all plants in this year. Then, the monthly energy efficiency data of different production plants with the monthly benchmark efficiency values of all plants in this year are compared and analyzed.

Step 4: The monthly ethylene production efficiency values for each year of different plants are weighted by AHP fusion to get annual ethylene production efficiency data of different plants.

Step 5: The annual ethylene production efficiency data of different plants are weighted by AHP fusion to obtain the benchmark efficiency values of this technology per year. Then, the annual energy efficiency data of different production plants with the benchmark efficiency values of this technology per year are compared and analyzed.

Step 6: Select the monthly data for different plants in another type of technology; run back to step 1, the loop will not stop until there is no technology which can be picked.

Step 7: The annual ethylene production efficiency data under different technologies were weighted by AHP fusion to get the benchmark efficiency value of the ethylene industry per year. Then, the annual ethylene production efficiency data under different technologies with the benchmark efficiency value of the ethylene industry per year are compared and analyzed.

Step 8: The ethylene production efficiency value per year of each technology were weighted by AHP fusion to find the ethylene production efficiency values of each technology in the last ten years, i.e., the efficiency values of steam, fuel, water, and electricity.

Fig. 2 illustrates the whole process of DEA and AHP for analyzing the energy efficiency of the ethylene industry.

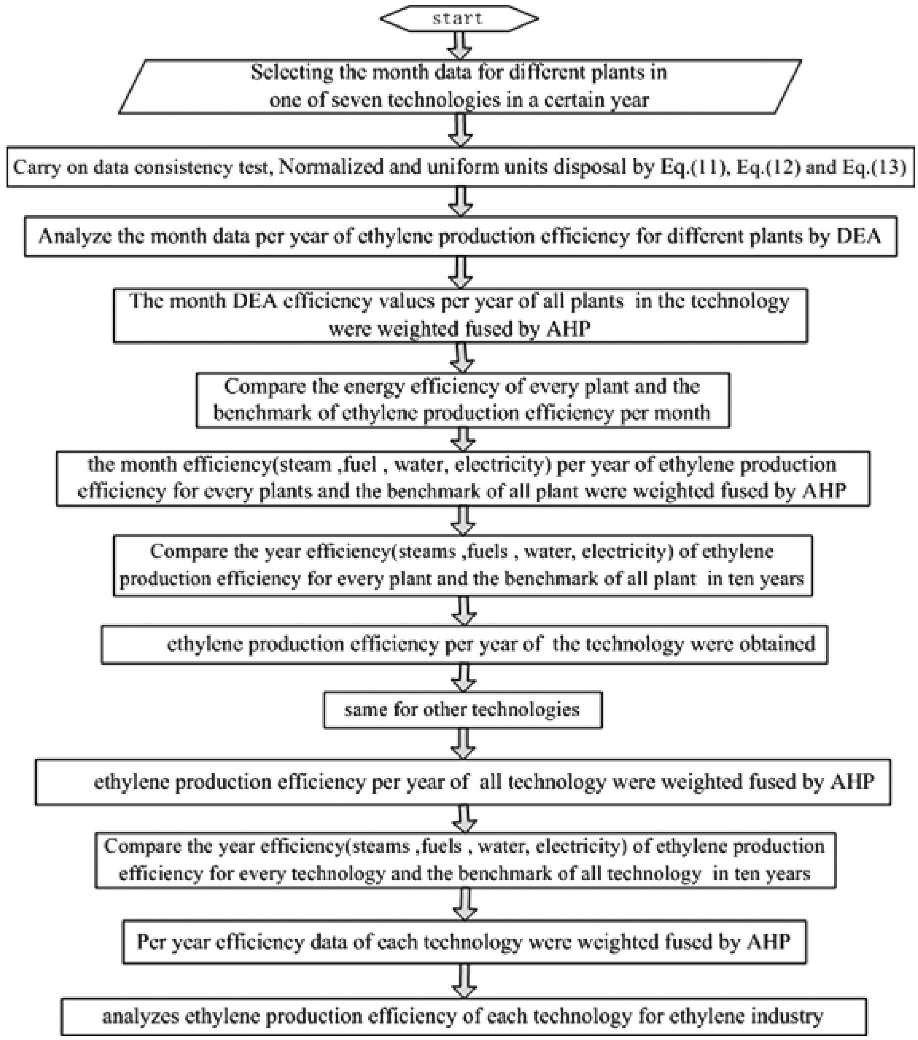

Figure 2. Flowchart of energy efficiency analysis of ethylene production equipment based on DEA and AHP.

4 Case Study: Energy Efficiency Analysis of the Ethylene Production Industry

In order to express the efficiency of ethylene production, it is important that the order separation technology is used in the empirical analysis. There are nine ethylene plants in China, which are Qilu, Fushun, Panjin, Yangtze, Dushanzi, Central Plains, Saike ethylene, Yanshan, and Tianjin ethylene, and the monthly data of energy efficiency in the last ten years came largely from those nine plants. In this paper, the data from 2010 are only employed to analyze the energy efficiency of ethylene plants under the order separation approach due to the huge number of total data. Fig. 3 is a plot of the whole fuels, steam, water, and electricity required of one ethylene plant in 2010, and Fig. 4 presents the monthly yields of ethylene and propylene of one ethylene plant in 2010.

First of all, in 2010, each ethylene plant required the resource of fuels, steams, water, and electricity as the model inputs, and

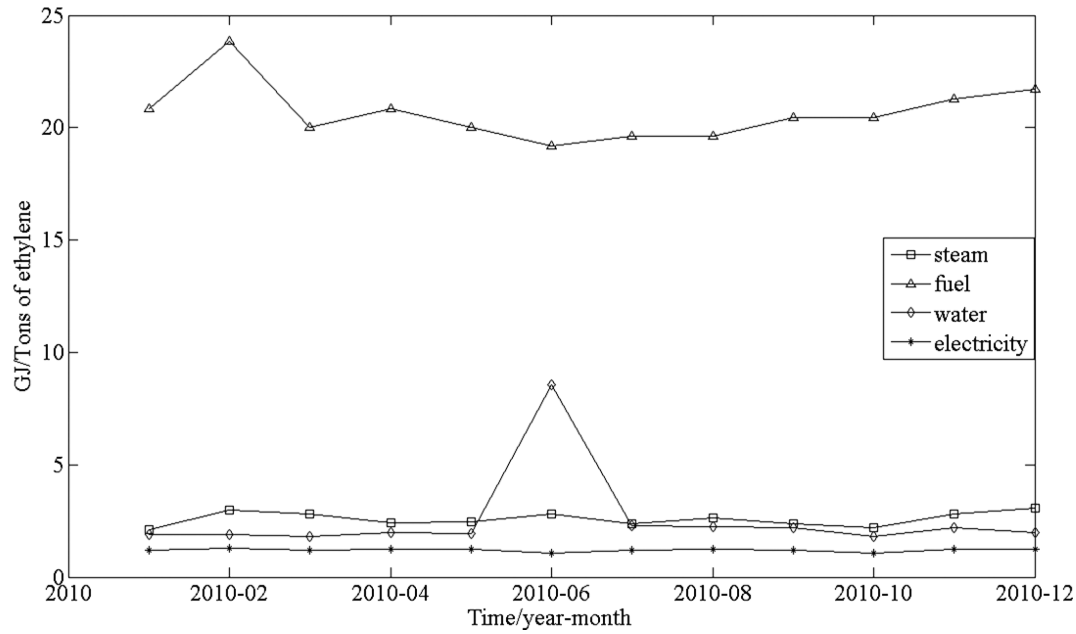

Figure 3. Required fuels, steams, water, and electricity of an ethylene plant in 2010.

the product yields of ethylene and propylene were the model outputs. Eq. (4) of the derived DEA model can provide monthly energy efficiency analytic values for every ethylene production plant under the order separation technology as displayed in Tab. 1.

According to Tab. 1, the energy efficiency values of January, March, June, July, August, and October in 2010 are 1, while the energy efficiency values of the other months have not reached the most efficient values. For example, the energy efficiency value of April is 0.9597. By analyzing slack variables of inputs and outputs, the conclusion is that the energy efficiency values of this month will be 1 if the usage of electricity decreases by 0.0718 GJ t^{-1} for each ethylene plant and the propylene yield increases by 0.0017. The same improvement direction can be obtained by analyzing the slack variables of other non-optimal months. Month, year, and the industry-level energy efficiency of every ethylene plant under different techniques and different scale will be considered in the following.

Secondly, using the input/output data above, the derived DEA model can produce monthly energy efficiency analytic values for every ethylene production plant under the order separation technology. The efficiency average values of the energy types of all ethylene plants per month can be obtained by AHP fusing DEA efficiency values of each plant per month. A comparison of the energy efficiency data of two ethylene production plants is presented in Fig. 5.

In Fig. 5 a, the steam, fuel, and electricity efficiency values of one plant are mostly higher than their average efficiency values of all plants. On the other hand, the water efficiency was generally lower than the average level, especially in June 2010. However, in March and October, the efficiencies of all energy types were better than the average level, in other words, the plant was doing well in those two months. Overall, the energy efficiency value of one plant in 2010 was better than the average level of all plants, and it was found significantly better in the first half of the year than the rest.

Fig. 5 b indicates that the electrical efficiency of another plant is much higher than the average electricity level of all plants, while the fuel efficiency value is lower than the average level. Moreover, the fluctuations of efficiency of water and steam are much greater than the others. In the first four months,

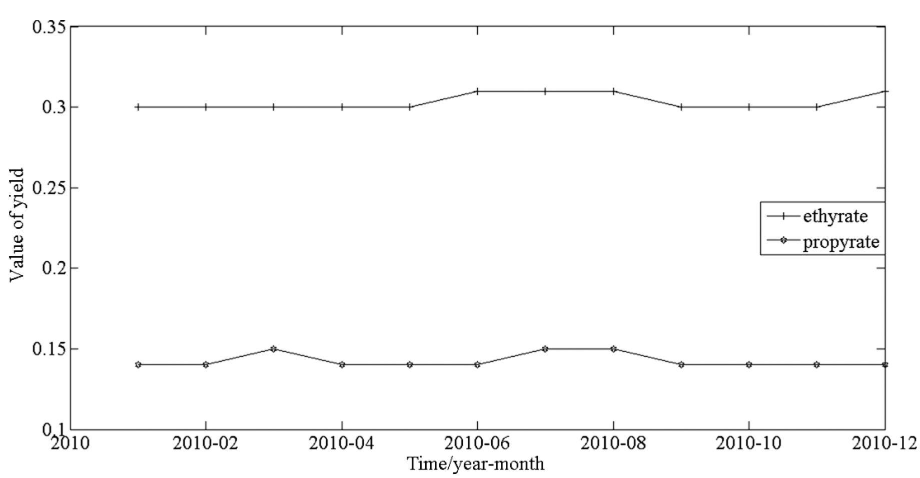

Figure 4. Monthly yield of ethylene and propylene of an ethylene plant in 2010.

Table 1. Monthly energy efficiency values and slack variables in 2010.

s^{1-}	s^{2-}	s^{3-}	s^{4-}	s^{1+}	s^{2+}	θ	Time
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	2010–01
0.3029	1.0000	0.0000	0.0664	0.0000	0.0000	0.9756	2010–02
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	2010–03
0.0000	0.0000	0.0000	0.0718	0.0000	0.0017	0.9597	2010–04
0.0000	0.0000	0.0000	0.0733	0.0000	0.0037	0.9936	2010–05
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	2010–06
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	2010–07
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	2010–08
0.0000	0.0000	0.0000	0.0287	0.0000	0.0035	0.9521	2010–09
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	2010–10
0.2869	0.0000	0.0000	0.0000	0.0000	0.0030	0.9210	2010–11
0.2912	0.0000	0.0000	0.0000	0.0000	0.0113	0.9597	2010–12

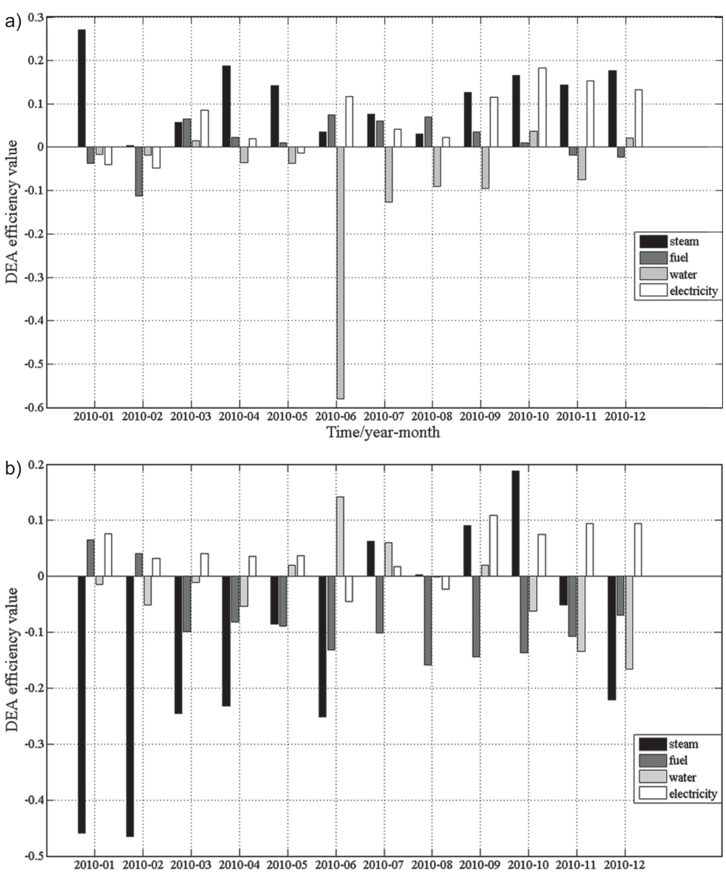

Figure 5. Energy efficiency ratio of two ethylene plants in 2010. The average of all ethylene plants is marked by the zero level.

the steam and water efficiency values were lower than the average level. In the next two months, however, the values suddenly reached a peak and then stayed at a low level during the rest of the year. The overall energy efficiency of the plant was lower than the average efficiency of all the plants. Comparing these two plants, based on the scale of ethylene production and some other reasons, the ethylene production situation of the plant in Fig. 5 a is better than that of the plant in Fig. 5 b in 2010.

The synthesized monthly energy efficiency data of each plant in 2010 was derived by AHP, and integrated efficiency data of various plants in different years could also be derived by the same method. Finally, the monthly weighted integrated data of energy efficiency can be employed to obtain the annual average efficiency value of different plants for the last ten years. Then, the benchmark efficiency values of the order separation technology for the last ten years are obtained by AHP. A comparison of the energy efficiency of two ethylene production plants and the average efficiency values of the energy types in the last ten years under the order separation technology are displayed in Fig. 6.

From 2001 to 2005, the ratio of the steam efficiency of the plant and the average steam efficiency of all plants decreased rapidly year by year (Fig. 6a). On the other hand, the efficiency ratio of the rest input resources, namely fuel, water, and electricity, increased in the first five years. However, after 2006, steam the energy efficient ratio (EER) value increased gradually, but fuel, water, and electricity EERs decreased annually based on the changes in EER data above. During 2006, because the scale and conditions of ethylene production plants were changed, the overall energy efficiency

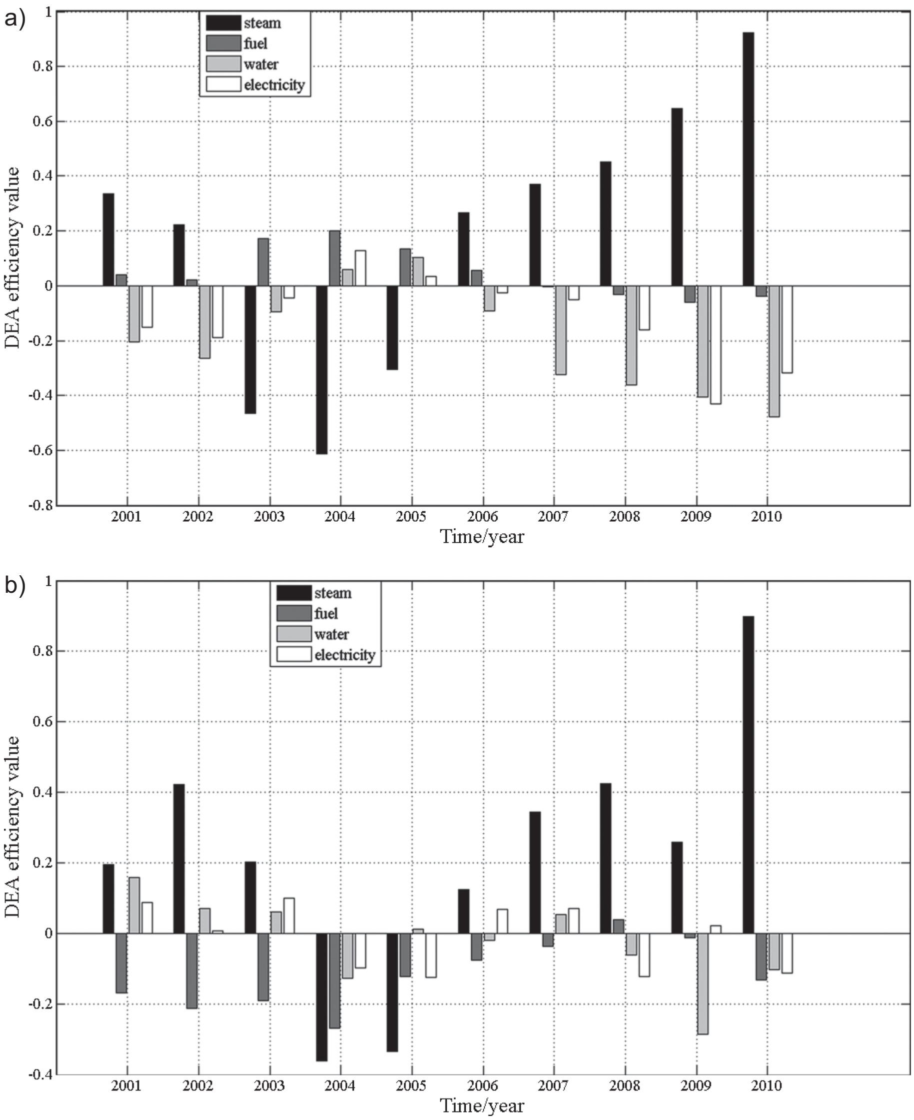

Figure 6. Annual integrated energy efficiency ratio of two ethylene plants in the last ten years.

Similarly, the annual energy efficiency data of each plant could be weighted integrated by AHP to get the annual average efficiency value under order separation technology in the last ten years, and the annual energy efficiency data of other technologies can be obtained in the same way. By fusing the annual efficiency value of seven technologies, the annual average energy efficiency data of the ethylene production industry can be obtained, as summarized in Fig. 7.

Fig. 7 a proves that the fuel, water, and electric efficiency of one technology is generally higher than the average efficiency of the overall technology in the last ten years, while the steam efficiency is lower than the steam average efficiency, except for 2003, 2004, and 2005. After 2006, the energy efficiency of fuel, water, and electricity gradually increased, while the energy efficiency of the steam declined year by year.

According to Fig. 7 b, the steam and fuel efficiency of this technology is higher than the average steam and fuel efficiency of the total technology. However, electricity efficiency was lower than the average before 2006. In 2002 and 2009, the situation was worse. In addition, the value of water efficiency was smaller than the water average efficiency as well. The graph provides the comparison of a pair of efficiency values, using the energy efficiency of two approaches and the overall technology, respectively. The water and electric energy efficiencies of the first technique are higher than the others, similarly, the steam and fuel efficiency of the second technique are better. Overall, the energy efficiency of the ethylene production indicates a distinct difference between the various technologies.

increased significantly though analyzing the volatility of energy consumption of ethylene production.

Fig. 6 b indicates that the ratio of the water and steam efficiency decreased year by year before 2005. From 2001 to 2003, the steam, water, and electricity efficiencies of the plant were higher than the average efficiency of all the plants. From 2003 to 2005, the type's efficiency was lower than the average energy efficiency. After 2006, the steam energy efficiency was higher than the average energy efficiency, and the other type's energy efficiencies of the plant fluctuated relatively.

According to the comparison of two plants and all plants, in 2005, the technology of each plant had adjusted in both scale and structure, leading to a significant change of raw material in the ethylene production. After 2005, the energy efficiency of the ethylene production increased. It can be concluded that the energy efficiency changed quite differently due to the distinctive scale of ethylene production under the same technique.

Based on the annul efficiency data of each technology in the last ten years, which are weighted integrated by AHP, the trends and states of energy efficiency under each technology are displayed in Fig. 8.

The DEA values in Fig. 8 indicate that the steam efficiency values of the second, fourth, and sixth class have improved in comparison to the other technologies. The steam production of the fifth technology of ethylene production is larger than the steam consumption, but the yields of ethylene and propylene are relatively lower, which cause the steam efficiency of the fifth technology to be the worst. In fuel efficiency, the fourth and the fifth are the best and the seventh is the worst. Therefore, com-

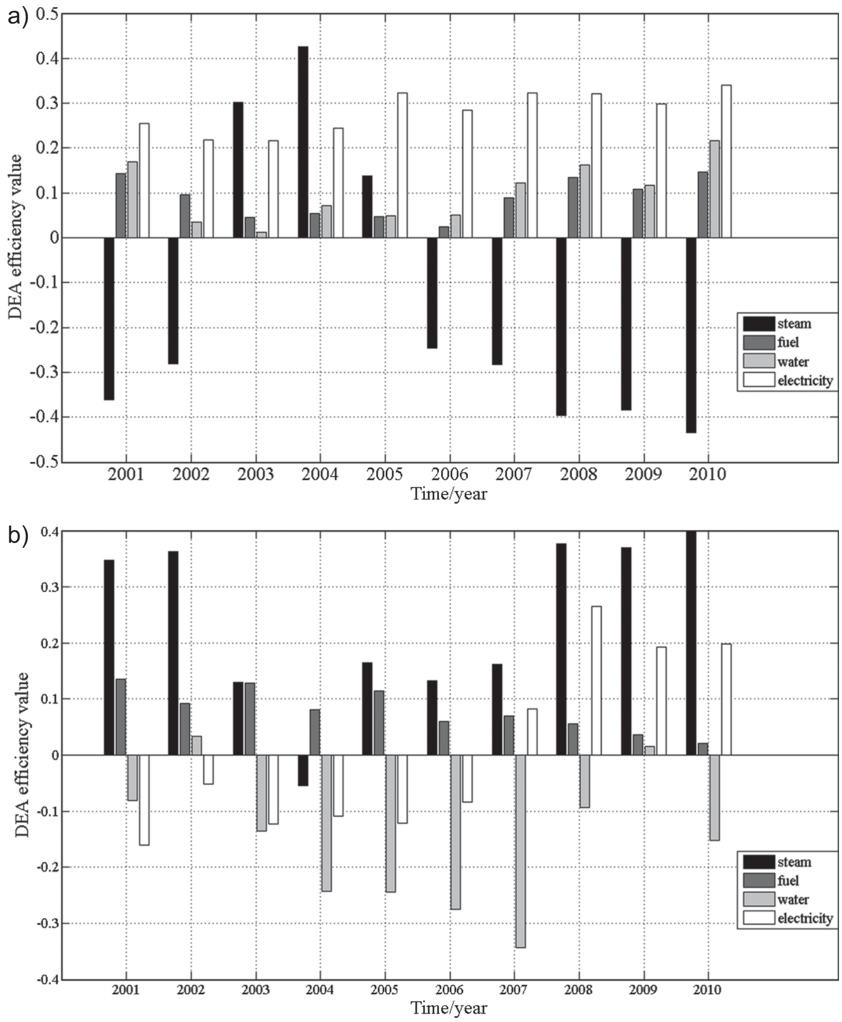

Figure 7. Annual integrated energy efficiency data of the (a) second and (b) fourth technology in the last ten years.

paring their differences of technologies with each other, one can also obtain the efficiency of water and electricity of different technologies. However, the overall outcomes of seven technologies are the same, which suggests that the ethylene production of these technologies is essentially the same. Because the energy demand and consumption costs of steam, fuels, water, and electricity are not the same in different regions, in the area of water sufficiency, the energy efficiency of ethylene production achieves the optimum by using the third technology, despite adopting the seventh technology is probably a better option. By the analysis above, the optimal choices of ethylene production for different plants may be based on the efficiency of local raw materials and energy production.

5 Conclusions

An energy efficiency evaluation framework based on an improved AHP method and DEA model with linear programming is proposed and verified by real energy data of practical ethylene plants. The traditional AHP based on a comparison matrix is the subjective fusion method, but the improved AHP established on differences in the data themselves can overcome the subjectivity shortcoming. Then the evaluation framework combined DEA and the improved AHP are applied to analyze the relationship of energy efficiency values of month and year between different technologies in production plants. The energy weights of plants are determined from the whole ethylene industry, so the energy efficiency in ethylene production could be evaluated objectively and energy efficiency conditions of different plants could be described, too. The proposed method has overcome the previous evaluation subjectivity of weights of each energy efficiency index and the disadvantage of too many inputs and outputs in DEA. The combined method has been proven to be able to objectively describe energy efficiency trends of different production plants. The DEA model also introduces slack variables to offer the opportunity and direction for energy saving in ethylene production, helping to improve saving measures for companies. Furthermore, this method is also applicable to energy efficiency evaluation of other plants in the petrochemical process.

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Symbols used

COR	n-order symmetric matrix
$k_{ij}(x)$	correlation function of the jth parameter in a plant
$K_{n\times m}$	information matrix
$R_{n\times m}{}^{j}$	positive matrix
s_t^-, s_t^+	slack variables
u	weight coefficients of s outputs
v	weight coefficients of m inputs
W	eigenvector
x_{ij}	i^{th} input of DMU$_{-j}$
$x_j(1)$, $x_j(2)$, $x_j(3)$, $x_j(4)$	nodes of $k_{ij}(x)$
y_{rj}	r^{th} output of DMU$_{-j}$

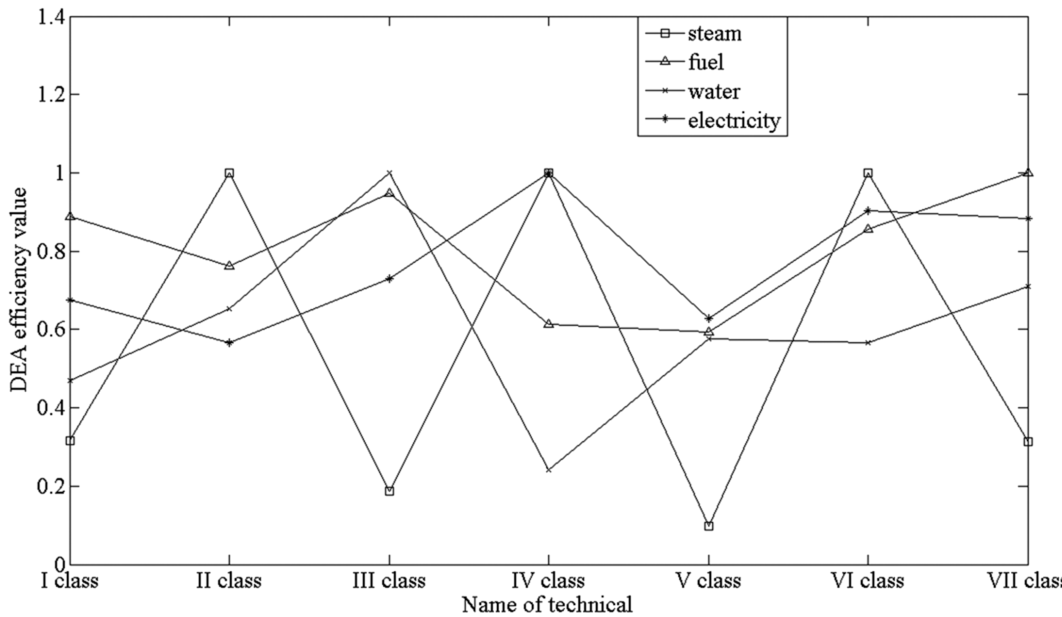

Figure 8. Average integrated energy efficiency data of ten years of different technologies.

Greek letters

ε	non-Archimedean infinitesimal
θ	optimum values of the DMU_{-j0}

Abbreviations

AHP	analytic hierarchy process
DEA	data envelopment analysis
DMU	decision making unit

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