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Energy Efficiency Evaluation Based on Data Envelopment Analysis Integrated Analytic Hierarchy Process in Ethylene Production☆

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ABSTRACT

Energy efficiency data from ethylene production equipment are of high dimension, dynamic and time sequential, so their evaluation is affected by many factors. Abnormal data from ethylene production are eliminated through consistency test, making the data consumption uniform to improve the comparability of data. Due to the limit of input and output data of decision making unit in data envelopment analysis (DEA), the energy efficiency data from the same technology in a certain year are disposed monthly using DEA. The DEA data of energy efficiency from the same technology are weighted and fused using analytic hierarchy process. The energy efficiency data from different technologies are evaluated by their relative effectiveness to find the direction of energy saving and consumption reduction.

1. Introduction

Ethylene production often plays an important role in evaluating the industrial development level of a country. According to the statistic results in 2005, naphtha, which accounts for 98% of ethylene cracking feeds, had its average comprehensive energy consumption of 29.3 GJ per ton ethylene. This consumption is 1.27 times higher than that of advanced production equipment in the world [1,2], so that ethylene industry in China has a great space for improving energy efficiency. The energy consumption cost accounts for more than half of the operation cost in ethylene production [3]. Researches on energy efficiency evaluation have great economic benefits. The most generally used evaluation index is the special energy consummation (SEC) per ton ethylene. The energy consumption is usually affected by feed composition, production technology, reconstructed size, load variation, *etc.*, but SEC does not take these factors into consideration.

In 1978, famous operation researchers A. Charnes, W. W. Cooper and E. Rhodes proposed the data envelopment analysis (DEA). They used this method to study "production apartment", which involved multiple inputs, especially multiple outputs, both "sizeable effective" and "technological effective". This application turned out to be satisfactory and effective [4]. To acquire highly objective results, consistency test, Paraffin, olefin, naphthenic and aromatic (PONA) of feed and uniformly dimensional disposal for total consumption of fuel, electricity, water and steam in ethylene production were conducted. This disposal not only eliminates abnormal data, but also increases the data comparability conveniently. Analytic hierarchy process (AHP) combines qualitative and quantitative analyses, which is a hierarchical and multi-criterion analytic method [5–8]. It meets the requirement of fusion of multiple solutions under multiple criteria of hierarchical mode of energy efficiency value. Faisal and Abdullahil [9] applied AHP model to select the most appropriate package of solar home system for rural electrification in Bangladesh. Opasanon and Lertsanti [10] implemented AHP to evaluate and rank the importance of logistic issues according to the needs and requirements of the policy makers of a company. Houshyar *et al.*[11] studied the energy consumption efficiency for corn production by utilizing DEA and AHP techniques. Geng *et al.*[12–15] used DEA model and AHP to evaluate energy efficiency of ethylene production system.

With respect to disadvantages in energy efficiency evaluation of ethylene industry in China [12–16] and the complex production situation of ethylene industry [17,18], a new evaluation method combining DEA and AHP is proposed in this paper. It is used to evaluate the comprehensive energy consumption in ethylene production with different technologies, presenting demonstration and reference to establish scientific benchmarks. And, it could be used to evaluate and analyze energy efficiency in petroleum chemical process reasonably and offer operation guidance for energy saving.

2. AHP Based on DEA

Ethylene cracking is a complicated process with different kinds of data, including operation data, simulation data, and design data. These

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data present complex nonlinear timing relationship among noise and abnormal points and so on [12]. Therefore, they need to be processed according to their characteristics, so as to assure their readiness, consistency and high precision. After data processing, multi-input and multi-output of DEA data and hierarchical fusion analysis could be established, with more accurate prediction and leading edge analysis.

2.1. Data preprocessing

Ethylene production data has complex nonlinear timing relationship among various factors, including noise and abnormal data. Dimensions of variables of timing data are usually different, which makes values of variables incomparable [13]. The data need to be tested for consistency and normalized. The following formula is used for long-length data and leads to erroneous judgment for short-length data [14].

$$T=\frac{|V|}{S}=\frac{|x_i-\bar{x}|}{S} \tag{1}$$

where $\bar{x}$ and S denote the mean and variance, respectively. Long-length data could be tested according to the Grubbs criterion: if $T \geq T(n,\alpha)$, x_i is eliminated, where n denotes the number of data and α is the significant level. The value of $T(n,\alpha)$ refers to literature [14].

Based on characteristics of energy efficiency data of ethylene production equipment, the general method to express its level is to convert measurement units of energy consumption parameters of fuel, electricity, water and steam into unit GJ, based on Tables 3.0.2 and 3.0.3 from Calculation Method for Energy Consumption in Petrochemical Engineering Design (SH/T3110-2001) [19]. The PONA values could not only effectively reflect common cracking characteristics of different feeds, but also remove the zero-value feed, by turning excessive feed inputs into P, O, N and A values. Thus the number of evaluation indexes is reduced, making input and output data of DEA analysis of energy efficiency more objective and universal.

The general transformation method is by proportion, in which the described subjects of timing data need to be paid attention. For the same subject, different variables make different interactions, some of which are positive [13,20], with the following conversion

$$x'_{ij}=\frac{x_{ij}}{x_j^{\max}} \tag{2}$$

while other variables are negative. The respective formulas are as follows

$$x'_{ij}=1-\frac{x_{ij}}{x_j^{\max}}+\left[1-\max_i\left(1-\frac{x_{ij}}{x_j^{\max}}\right)\right] \tag{3}$$

where $x_j^{\max}=\max\{x_{1j}, x_{2j}, \ldots, x_{ij}\}$, $i=1, 2, \ldots, t$, $j=1, 2, \ldots, m$.

2.2. DEA linear programming model

The first model of DEA analysis is named C^{2}R model, shown briefly as follows.

There are n departments or units, namely decision making unit (DMU). Each DMU has m inputs and s outputs, in which $x_j=(x_{1j}, x_{2j}, \ldots, x_{mj})^{\mathrm{T}}>0$, $y_j=(y_{1j}, y_{2j}, \ldots, y_{sj})^{\mathrm{T}}>0$, x_{ij} equals jth input to ith input of DMU, y_{ij} equals jth output to rth output of DMU ($j=1,2,\ldots,n$; $i=1,2,\ldots,m$; $r=1,2,\ldots,s$). DMU $-j_0$ has its corresponding input and output data with $x_0=x_{j0}$, $y_0=y_{j0}$, $1\leq j_0\leq n$. The DEA model (C^{2}R) for evaluating DMU $-j_0$ is expressed as fractional programming by

$$\begin{cases} \max \dfrac{u^{\mathrm{T}}y_0}{v^{\mathrm{T}}x_0} \\ \dfrac{u^{\mathrm{T}}y_j}{v^{\mathrm{T}}x_j}\leq 1.j=1,2,\ldots,n \\ u\geq 0, v\geq 0, u\neq 0, v\neq 0 \end{cases} \tag{4}$$

where $v=(v_1,v_2,\ldots,v_m)^{\mathrm{T}}$ and $u=(u_1,u_2,\ldots,u_s)^{\mathrm{T}}$ represent the weight coefficients of m inputs and s outputs, respectively. The Charnes–Cooper transformation formula for fractional programming, proposed by Charnes and Cooper in 1962, is used here,

$$t=\frac{1}{v^t x_0}>0, w=tv, \mu=tu. \tag{5}$$

The fractional model (C^{2}R) could be transformed into equivalent linear programming,

$$\begin{cases} \max \mu^{\mathrm{T}}y_0=v^0, \\ w^{\mathrm{T}}x_j-\mu^{\mathrm{T}}y_j\geq 0, j=1,2,\ldots,n, \\ w^{\mathrm{T}}x_0=1, \\ w\geq 0, \mu\geq 0 \end{cases} \tag{6}$$

$$\begin{cases} \min \theta, \\ \sum_{j=1}^{n} x_j\lambda_j\leq\theta x_0, \\ \sum_{j=1}^{n} y_j\lambda_j\geq y_0, \\ \lambda_j\geq 0, j=1,2,\ldots,n, \theta\in E^1. \end{cases} \tag{7}$$

If the optimum objective value of Eq. (6) v^0 equals 1, DMU $-j_0$ is DEA weak effective (v^0 is the efficiency index). Calculated by the linear programming of Eq. (7), optimum values θ^* and λ^* are obviously less than 1. This model indicates whether the linear combination of all DMU could be found or not. Thus, if $\theta^*<1$, DMU $-j_0$ is DEA ineffective; if $\theta^*=1$, DMU $-j_0$ is effective or weak effective according to whether the two constrained inequalities are satisfied. All DMUs that are DEA effective constitute the production effective frontier. The lesser the θ^*, the farther it is from the frontier, and the lower the relative efficiency [21].

The above model shows that the efficiency of DEA is relative. Since the DEA model could describe the production frontier as long as multi-input and multi-output data are given, the accuracy of analysis results is easily affected by DMU input and output data and their precision. Thus input and output data need to be preprocessed to improve the accuracy of description of ethylene production frontier by the DEA model.

2.3. AHP model based on correlation function

Subjectivity of the traditional AHP, which compares the relationship between data, is strong, but the AHP model based on the correlation function avoids the subjective analysis and can assign different weights on data more objectively. The algorithm is shown as follows.

Definition 1: Let the correlation function of the jth parameter in the equipment be $\boldsymbol{k}_{ij}(x)$ (from the ith sample), then the correlation function is called trapezoidal correlation function, with $x_j(1)$, $x_j(2)$, $x_j(3)$, and $x_j(4)$ as the nodes of $\boldsymbol{k}_{ij}(x)$.

$$\boldsymbol{k}_{ij}(x)=\begin{cases}0 & x\notin\left[x_j(1),x_j(4)\right]\\ \dfrac{x_{ij}-x_j(1)}{x_j(2)-x_j(1)} & x\in\left[x_j(1),x_j(2)\right]\\ 1 & x\in\left[x_j(2),x_j(3)\right]\\ \dfrac{x_j(4)-x_{ij}}{x_j(4)-x_j(3)} & x\in\left[x_j(3),x_j(4)\right]\end{cases}\quad i=1,2,\ldots,n;j=1,2,\ldots,m. \tag{8}$$

If the second and third nodes $x_j(2)$ and $x_j(3)$ of the standard correlation function coincide, $\boldsymbol{k}_{ij}(x)$ is tangle correlation functions [22,23].

Let the energy efficiency timing data after preprocessing be $X=[X(1)\quad X(2)\quad \ldots\quad X(n)]^{\mathrm{T}}$, whereas $X(i)$ is the energy efficiency value of ethylene production at moment $t=i$. The underside correlation function is adopted here, and $x_j(2)(j=1,2,\ldots,m)$ is the average value. The information matrix $\boldsymbol{K}_{n\times m}$ is deprived as

$$\boldsymbol{K}_{n\times m}=\begin{bmatrix}k_{11} & k_{12} & \ldots & k_{m1}\\ k_{21} & k_{22} & \ldots & k_{m2}\\ \ldots & \ldots & \ldots & \ldots\\ k_{n1} & k_{n2} & \ldots & k_{nm}\end{bmatrix}. \tag{9}$$

After centralizing and normalizing, information data are transformed to $k'_{ij}\left(k_{ij}-\overline{k_j}\right)/S_j$, $i=1,2,\ldots,n$; $j=1,2,\ldots,m$, where $\overline{k_j}=\frac{1}{n}\sum_{i=1}^{n}k_{ij}$ and $S_j=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(k_{ij}-\overline{k_j}\right)}$. Then, all the negative values are shifted to zero (negative zero plus a positive decimal value ε), i.e., $r_{ij}=k'_{ij}-t_j+\varepsilon$, wherein $t_j=\min(k'_{ij})<0$. A positive matrix $\boldsymbol{R}^{j}_{n\times m}$ and an n-dimension matrix are derived

$$\boldsymbol{R}^{j}_{n\times m}=\begin{bmatrix}r_{11} & r_{12} & \ldots & r_{1m}\\ r_{21} & r_{22} & \ldots & r_{2m}\\ \ldots & \ldots & \ldots & \ldots\\ r_{n1} & r_{n2} & \ldots & r_{nm}\end{bmatrix} \tag{10}$$

$$\mathbf{COR}=\boldsymbol{RR}^{\mathrm{T}}=\begin{bmatrix}o_{11} & o_{12} & \ldots & o_{1n}\\ o_{21} & o_{22} & \ldots & o_{2n}\\ \ldots & \ldots & \ldots & \ldots\\ o_{n1} & o_{n2} & \ldots & o_{nn}\end{bmatrix}. \tag{11}$$

For the n-order symmetric matrix **COR**, its eigenvector or $\boldsymbol{W}=(w_1,w_2,\ldots,w_n)^{\mathrm{T}}$ is derived through geometric mean method as follows:

$$|\boldsymbol{WE}-\mathbf{COR}|=0 \tag{12}$$

where

$$\boldsymbol{E}=\begin{bmatrix}1 & 0 & \ldots & 0 & 0\\ 0 & 1 & \ldots & 0 & 0\\ \ldots & \ldots & \ldots & \ldots & \ldots\\ 0 & 0 & \ldots & 0 & 1\end{bmatrix}_{n\times n} \tag{13}$$

is $n\times n$ identity matrix. Using vector $\boldsymbol{W}$ to integrate schemes gives the integration data $\boldsymbol{X}_{\mathrm{ref}}$ of energy efficiency values of ethylene production.

$$\boldsymbol{Y}=\begin{bmatrix}y_1\\ y_2\\ \ldots\\ y_m\end{bmatrix}^{\mathrm{T}}=\boldsymbol{X}^{\mathrm{T}}\boldsymbol{W}=\begin{bmatrix}x_{11} & x_{12} & \ldots & x_{1m}\\ x_{21} & x_{22} & \ldots & x_{2m}\\ \ldots & \ldots & \ldots & \ldots\\ x_{n1} & x_{n2} & \ldots & x_{nm}\end{bmatrix}^{\mathrm{T}}\begin{bmatrix}w_1\\ w_2\\ \ldots\\ w_n\end{bmatrix}. \tag{14}$$

3. Energy Efficiency of Ethylene Production

The ethylene production is a multi-input and multi-output process. Its abnormal data and noise could be rejected through consistency test, uniform dimension disposal of units and PONA value calculation of main feedstock. After data disposal, the multi-input and multi-output data could be sorted more accurately and objectively. The energy efficiency evaluation for ethylene production equipment could be more accurate through the DEA model and AHP analyses. All these point out the way of disposing feed costs with different production technologies for different companies and improving production design and energy efficiency, and then increase outputs.

The energy efficiency analysis procedure for ethylene production equipment based on DEA and AHP is described as follows.

Step 1: Select energy consumption data of the same technology in different equipment and carry out data consistency test and uniform unit disposal by Eqs. (1)–(3).

Step 2: Analyze the data of 12 months in each equipment by DEA.

Step 3: Integrate energy consumption data by weights of AHP in 12 months for DEA values in every year.

Step 4: Integrate monthly consumption data of the technology by weights of AHP, and then obtain the fusion energy consumption values of steam, water, electricity and fuel.

Step 5: Integrate each consumption data of the technology by weights of AHP, and then obtain the fusion energy consumption values of the technology per year.

Step 6: Obtain the same energy consumption value for other technologies, and then get efficiency trends of technologies in the latest 10 years.

Step 7: Integrate yearly energy efficiency data by AHP, sort out, and analyze efficiency data of all technologies.

Fig. 1 gives the energy efficiency analysis process of ethylene production equipment based on DEA and AHP.

The annual or monthly energy efficiency data are added directly, without considering the distribution of each weight. AHP hierarchical model fuses the energy efficiency data with every technology, without considering the effect of the major crude oil (naphtha, hydrogenated tail oil and so on) on the water, electricity, steams and fuels [12,16,21,24]. The obtained fusion results cannot represent the energy efficiency accurately required by the ethylene production with only one technology. The algorithm here considers the effect of crude oil and the DEA model takes the objective analysis results as the weights of AHP. Table 1 shows the features of different methods introduced in this paper.

Monthly production data of the latest ten years of more than 20 ethylene production companies are used in this paper as the analysis object. First, all data related to energy efficiency are preprocessed for data rejection and dirty data removal, getting energy efficiency data of different sizes under different technologies. Second, these different data are analyzed by the DEA model, making analysis results more accurate and objective. According to ethylene production process, taking effects of different feeds on water, steam, fuel and electricity consumption into consideration, the sum of consumption is used as the model input, while product yields of ethylene and propylene are as the model output.

The monthly DEA efficiency values of different ethylene equipment with a technology in 2010 are shown in Fig. 2. In general, the energy efficiency value of each plant remained above 0.8, but that of plant 2 in May 2010 was only 0.38. By ethylene production data, we know that plant 2 cut production for equipment maintenance in March. All plants reached the top ethylene production scale in October 2010 and can use these data as the benchmark to guide ethylene production, reducing energy consumption and improving energy efficiency.

Table 2 also gives ethylene production energy efficiency data of a plant. The energy efficiency value of plant 5 reached the highest in

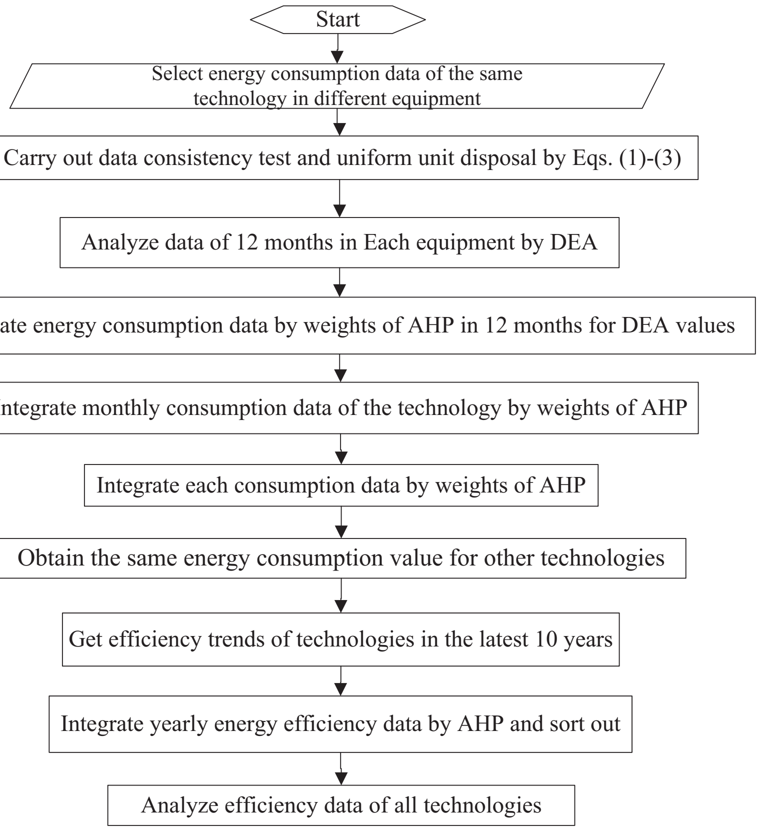

Fig. 1. Flowchart of energy efficiency analysis for ethylene production equipment with DEA model and AHP.

January, May and October, and the lowest in November. Energy data in November, compared with those in October, were mainly due to water, electricity, steam, and fuel consumption added, while the yield of ethylene and propylene were unchanged. Compared with January and May, plant 5 reduced fuel and water consumptions and increased the yield of ethylene or propylene in November. Similarly, we can improve energy efficiencies of other plants by comparing with the optimal process production efficiency.

The derived DEA data model could produce monthly energy efficiency values for all ethylene production companies. Integrate the production scales of different companies in the same year using the same technology by AHP to get corresponding weights for companies.

These weights are multiplied by the DEA results to get the first-layer integration data of monthly energy efficiency values. Seven common process technologies are used in ethylene production in China [15]:

Table 1
The features of different methods introduced in this paper

Method	Characteristics
Simple sum	① Simple and convenient ② Strong subjectivity, not considering data weights among different ethylene plants
AHP	① More objective, weights distributing better ② Not considering the effect of crude oil on the energy consumption such as water, electricity, steam and fuel
DEA	① Objective, considering the effect of crude oil on the ethylene production energy consumption, water, electricity, steam and fuel ② Multi-input and multi-output, decision-making units having restrictions
DEA-AHP	① Objective, considering the effect of crude oil on the energy consumption such as water, electricity, steam and fuel ② Avoiding restrictions of multi-input and multi-output and decision-making units

(1) KBR front-end depropanization and front adding hydrogen technology, (2) Linde front-end deethanization technology, (3) Lummus order separation technology, (4) S&W front-end depropanization and front adding hydrogen technology, (5) TPL patent technology, (6) Dalian University technology, and (7) Mitsubishi heavy industries front-end epropanization and behind adding hydrogen technology. We take one technology as an example to illustrate the validity of the proposed method. Fig. 3 shows the integration data by months in 2010 from one technology.

Then, the synthesized monthly energy efficiency data in 2010 are derived by AHP. In the same way, integrated efficiency data in other years could be derived. Finally, monthly energy efficiency data are weighted and integrated by AHP to get the average efficiency value for

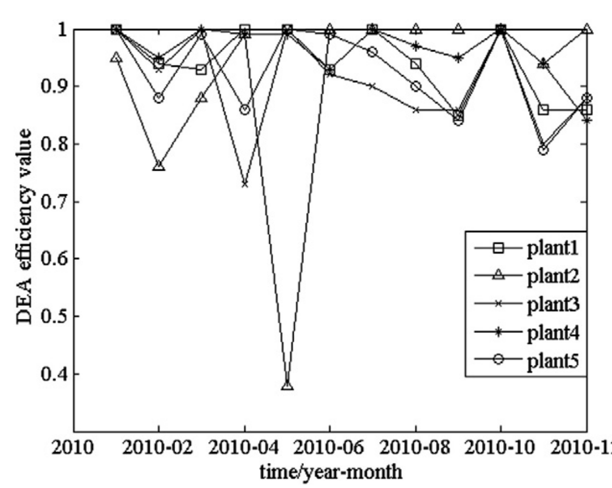

Fig. 2. The monthly DEA efficiency values of different ethylene production equipment.

Table 2
Energy efficiency data and DEA efficiency values of plant 5

PONA	Steam	Fuel	Water	Electricity	Ethyrate	Propyrate	Value	Time
3.16	2.8	20.02	1.82	1.2	0.3	0.15	1	2008–01
3.16	2.4	20.86	1.98	1.23	0.3	0.14	0.88	2008–02
3.08	2.13	20.86	1.88	1.2	0.3	0.14	0.99	2008–03
3.13	2.99	23.85	1.9	1.27	0.3	0.14	0.86	2008–04
3.10	2.83	19.19	1.85	1.07	0.31	0.14	1	2008–05
3.05	2.44	20.02	1.93	1.22	0.3	0.14	0.99	2008–06
2.95	2.36	19.62	2.3	1.19	0.31	0.15	0.96	2008–07
2.92	2.64	19.61	2.23	1.26	0.31	0.15	0.9	2008–08
3.06	2.37	20.44	2.19	1.21	0.3	0.14	0.84	2008–09
3.10	2.18	20.44	1.8	1.06	0.3	0.14	1	2008–10
3.15	2.79	21.28	2.21	1.22	0.3	0.14	0.79	2008–11
2.99	3.08	21.69	1.96	1.24	0.31	0.14	0.88	2008–12

every year in the latest ten years. Fig. 4 describes the integrated energy efficiency data in latest 10 years of different technologies.

Taking technology (3) for example, it is obvious that the energy efficiency decreased between 2002 and 2004 and increased later because of a larger company scale. Based on the results of 2009, technology (4) had the lowest energy efficiency while technology (5) had the highest. Technology (4) had the highest DEA efficiency value of ethylene production. These efficiency data are integrated by AHP by years to get the average value.

Fig. 5 shows that the energy efficiency of technology (6) is far higher than that of other technologies, while those of technologies (1), (5) and (3) arerelatively lower, which should be improved for energy consumption costs of feed, steam, water, electricity and fuel, as well as ethylene production qualities. Or these companies could improve the production technologies to reduce energy consumption and increase ethylene and propylene yields.

Most ethylene plants use the SEC as the energy efficiency index, which is the energy needed for producing 1 ton ethylene, GJ per ton ethylene, reflecting the energy consumption level to some extent [16]. The SEC is obtained by summing the consumptions of water, steams, powers and fuels. The annual energy consumption with technology (3) is obtained by the AHP. Figs. 6 and 7 show the annual data, mainly including PONA values, SEC and yields of ethylene and propylene from two ethylene plants with technology (3) for ten years. Comparing the date in 2005 with that in 2010 in Fig. 6, we see that the PONA value of raw material oil increased from 3.2 to 3.46 per ton ethylene and the SEC decreased by 10%, while the yield of ethylene and propylene increased from 0.446 to 0.463. From 2001 to 2005, the PONA value of raw material oil was less than 3.3 per ton ethylene, the SEC was much higher than 30.1 GJ per ton ethylene, while the yields of ethylene and propylene were lower than 0.449. After 2006 the ethylene plant increased the PONA value and reduced the SEC, with the yield of ethylene and propylene increased year by year. Similarly, Fig. 7 shows energy saving and ethylene production increase in another plant. From 2001 to 2005, its ethylene yield and SEC savings were less than those in Fig. 6, and after 2006, the plant reduced SEC to 28.5 GJ per ton ethylene and increased the crude oil PONA value, improving the ethylene energy efficiency and catching ethylene yield in the plant in Fig. 6. All these improvements are according to energy efficiency evaluation based on DEA integrated AHP of ethylene technology.

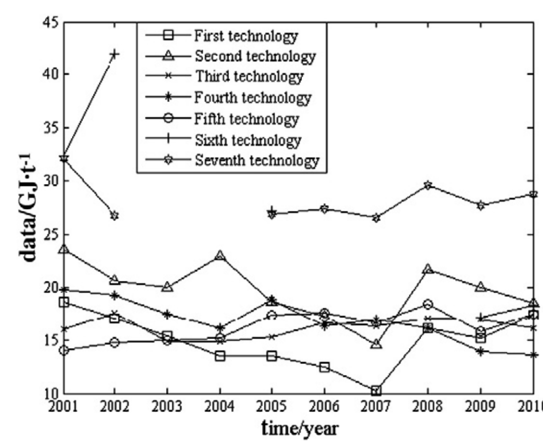

Fig. 4. Yearly integrated energy efficiency data in latest 10 years of different technologies.

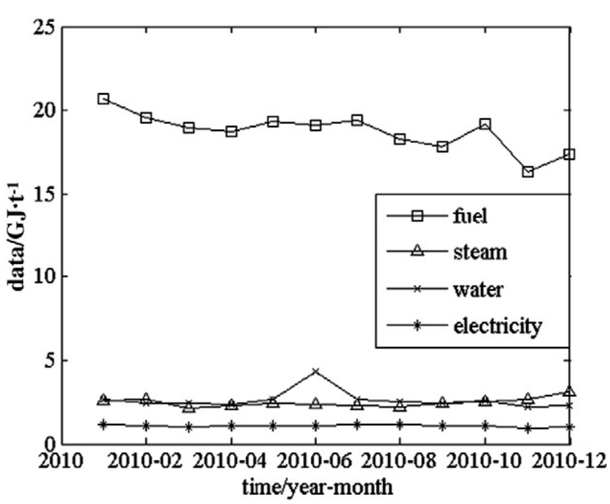

Fig. 3. Integration data by months in 2010 from one technology.

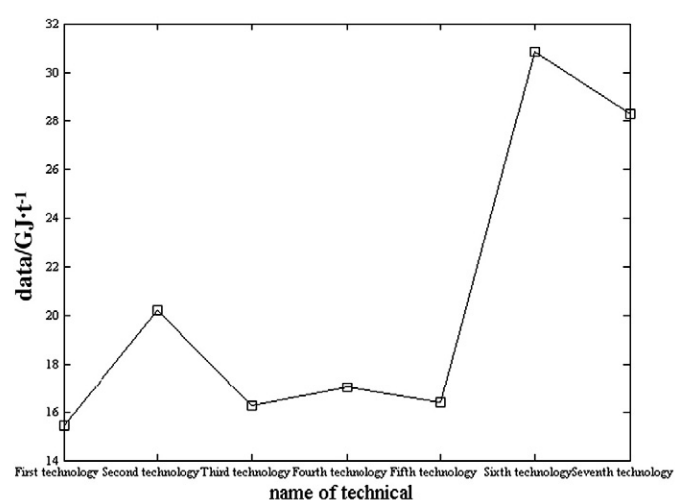

Fig. 5. Average integrated energy efficiency data of ten years of different technologies.

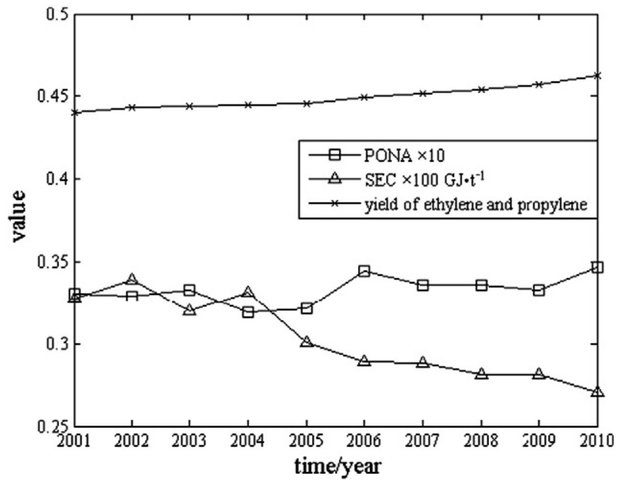

Fig. 6. The values of PONA, SEC and yield of ethylene and propylene of one ethylene plant in ten years.

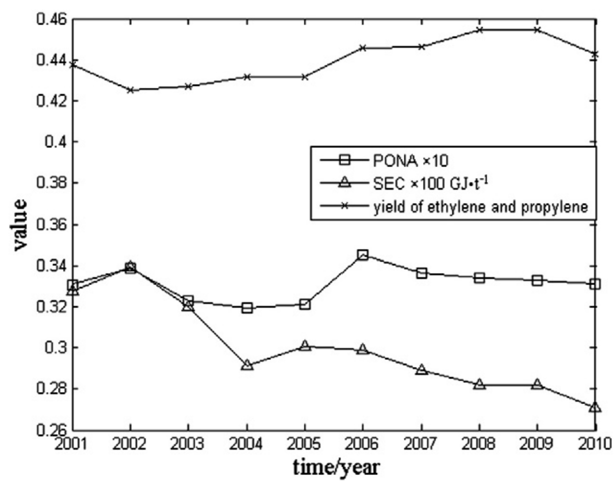

Fig. 7. The values of PONA, SEC and yield of ethylene and propylene of another ethylene plant in ten years.

4. Conclusions

We combine DEA and AHP and propose the relationship of energy efficiency values of months and years between different technologies in ethylene production equipment. The scale weights of equipment are analyzed in the whole scale, so the energy consumption in ethylene production could be analyzed objectively and energy efficiency conditions of different equipment could be described. This 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 can describe energy efficiency trends of different production equipment, with effectiveness and usability. It also offers the opportunity and direction for energy saving in ethylene production, helping to improve saving measures for companies. This method is also applicable to energy efficiency evaluation of other equipment.

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