Chinese Journal of Chemical Engineering 23 (2015) 2029–2036

Contents lists available at ScienceDirect

Chinese Journal of Chemical Engineering

journal homepage: www.elsevier.com/locate/CJChE

Energy consumption hierarchical analysis based on interpretative structural model for ethylene production☆

Yongming Han, Zhiqiang Geng *, Qunxiong Zhu, Xiaoyong Lin

College of Information Science and Technology, Beijing University of Chemical Technology, Beijing 100029, China
Engineering Research Center of Intelligent PSE, Ministry of Education in China, Beijing 100029, China

ARTICLE INFO

Article history:
Received 20 May 2015
Received in revised form 30 June 2015
Accepted 17 July 2015
Available online 10 November 2015

Keywords:
Partial correlation coefficient
Interpretative structural model
Energy consumption
Hierarchical analysis
Ethylene production
Chemical processes

ABSTRACT

Interpretative structural model (ISM) can transform a multivariate problem into several sub-variable problems to analyze a complex industrial structure in a more efficient way by building a multi-level hierarchical structure model. To build an ISM of a production system, the partial correlation coefficient method is proposed to obtain the adjacency matrix, which can be transformed to ISM. According to estimation of correlation coefficient, the result can give actual variable correlations and eliminate effects of intermediate variables. Furthermore, this paper proposes an effective approach using ISM to analyze the main factors and basic mechanisms that affect the energy consumption in an ethylene production system. The case study shows that the proposed energy consumption analysis method is valid and efficient in improvement of energy efficiency in ethylene production.

1. Introduction

Petrochemical industry is one of the highest energy consumption sources such as power, fresh water, fuels, and steam. Ethylene production plays an important role in petrochemical industry. In 2008, the ethylene production capacity of Sinopec Corporation was 6359.4 kt and the energy consumption of ethylene plants was 649.36 kg · t^{-1} standard oil [1]. Petro China Company Ltd. had 2676 kt product with 714 kg · t^{-1} standard oil [2]. The energy consumption is much higher than that in the developed countries, so there is a huge space to improve the energy efficiency in ethylene industry [3]. The energy consumption analysis for ethylene production can bring a good economic benefit.

In recent years, reduction of energy consumption and emission in ethylene production has been highly concerned. Energy-saving situations are improved by using advanced control techniques, optimized operation conditions, and ancillary facilities [4–7]. The energy consumption in ethylene industry can be reduced by energy management and process integration [8,9]. However, the implementation procedure is complicated and tedious, and the effect can be verified only with practical projects or particular process simulations.

Tang evaluated the economic benefit of various light hydrocarbon resources for ethylene plant using a process industry modeling system [10]. Zhu *et al.* proposed energy consumption analysis based on data fusion strategy [11–13]. Xu *et al.* studied energy consumption and emission for an ethylene plant with different start-up strategies by plant-wide dynamic simulations [14,15]. These data-driven based efficiency analyzing approaches can give good results, but they ignore the effect of raw materials, which are strongly related to energy consumption, especially in ethylene production processes.

To avoid these drawbacks, it is necessary to have a more effective analysis method for energy consumption by integrating the process knowledge and simulation results, as well as the data-driven methods, with less complexity and cost of analysis and more reliable evaluation.

In 1973, Warfield developed the interpretive structural model (ISM) to analyze complex systems [16]. The barriers in a hierarchical structure of production service system, supply chains and quality management were analyzed with ISM [17–20]. Govindan *et al.* used the ISM to analyze the third party reverse logistics provider [21]. These results proved the practicality and effectiveness of ISM. Ethylene production is a complex industrial process with a lot of variables, so ISM can be used to construct a hierarchy model based on energy consumption data. It can utilize accessible daily operation data to establish reliable variable correlations, making the energy consumption analysis more reliable, while the complexity of modeling can be avoided.

The initial step to establish an ISM is to create an adjacency matrix using experts' experience, with shortcoming of subjectivity and inconsistency. The ISM of energy consumption for an ethylene plant is

☆ Supported by the National Natural Science Foundation of China (61374166, 6153303), the Doctoral Fund of Ministry of Education of China (20120010110010), and the Fundamental Research Funds for the Central Universities (YS1404, JD1413, ZY1502).
* Corresponding author.
E-mail address: gengzhiqiang@mail.buct.edu.cn (Z. Geng).

http://dx.doi.org/10.1016/j.cjche.2015.11.011
1004-9541/

constructed based on date-driven method with process knowledge and mechanism model. In data analysis, Yu *et al.* have found that the partial correlation function is more realistic to reflect the relationship among variables [22]. Vargha *et al.* discussed interpretation problems of the partial correlation with non-normally distributed variables [23]. Fan *et al.* used the correlation coefficient method to verify the efficiency of signed directed graph model [24]. Other researchers studied the partial correlation coefficients and achieved positive results in the closed-loop optimal experiment, permutation test, and copula function modeling [25–27]. Therefore, based on the adjacency matrix of correlation coefficients and partial correlation coefficients, the reachability matrix can be obtained, and then the ISM can be applied for energy consumption in ethylene production systems.

By analyzing a large number of accessible daily operation data and considering the complexity of an ethylene plant in modeling process, we propose an effective approach using ISM based on the partial coefficients to analyze the main factors and basic mechanisms affecting the energy consumption. A case study is used to evaluate the proposed energy consumption analysis method.

2. ISM Based on Partial Correlation Coefficients

The ISM is based on the partial coefficient analysis for different elements. It can find the relationship among variables, avoid influences of irrelevant variables, and remove influences of subjective factors. The ISM is built with data-driven based analysis, because the procedure to obtain adjacency matrix is objective and consistent.

2.1. The partial correlation coefficient matrix

The correlation coefficient based approach only considers the relationship between two variables, so it is seldom used to infer the relationship between variables directly. Moreover, other factors with the relationship should be considered. By contrast, the partial correlation relationship deducts or fixes the effect of other variables beside the relationship of two variables. The linkages of variables are evaluated by partial correlation coefficients [5]. The greater the absolute value of a partial correlation coefficient is, the stronger the relationship between two variables will be. It reflects the correlation between dependent and independent variables, with the number between −1 and 1. Hence, we use its absolute value generally.

Let x_i ($i = 1, 2, \ldots, m$) be the ith value of variable x, then the correlation coefficient of x_i and y_i is

$$r_{xy} = \frac{\sum_{i=1}^{M}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{M}(x_i-\bar{x})^2}\sqrt{\sum_{i=1}^{M}(y_i-\bar{y})^2}} \tag{1}$$

where $\bar{x}$ and $\bar{y}$ are the mean values of x and y, respectively.

The correlation coefficient matrix is

$$\boldsymbol{r} = \begin{bmatrix} r_{11} & r_{12} & \ldots & r_{1n-1} & r_{1n} \\ r_{21} & r_{22} & \ldots & r_{2n-1} & r_{2n} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ r_{m1} & r_{m2} & \ldots & r_{m-1n-1} & r_{mn} \end{bmatrix}_{m\times n.} \tag{2}$$

Its inverse matrix $\boldsymbol{c}$ is used to obtain the partial correlation coefficient matrix.

$$\boldsymbol{c} = \mathrm{inv}(r) = \begin{bmatrix} c_{11} & c_{12} & \ldots & c_{1n-1} & c_{1n} \\ c_{21} & c_{22} & \ldots & c_{2n-1} & c_{2n} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ c_{m1} & c_{m2} & \ldots & c_{m-1n-1} & c_{mn} \end{bmatrix}_{m\times n.} \tag{3}$$

The partial correlation coefficient between two variables is

$$R_{ij} = -\frac{c_{ij}}{\sqrt{c_{ii}\times c_{jj}}} \quad (i = 1, 2, \ldots, m; j = 1, 2, \ldots, m). \tag{4}$$

There are different definitions about whether the partial correlation coefficient is related in different industries. Table 1 shows the relationship and the scope of partial correlation coefficients [28].

Table 1
The scope of partial correlation coefficient

Partial correlation coefficient	Relationship between two variables
$0 \le \lvert R_{ij}\rvert < 0.1$	No relationship
$0.1 \le \lvert R_{ij}\rvert < 0.3$	Low correlation
$0.3 \le \lvert R_{ij}\rvert < 0.5$	Medium correlation
$0.5 \le \lvert R_{ij}\rvert < 0.8$	Strong correlation
$0.8 \le \lvert R_{ij}\rvert \le 1$	Extremely strong

2.2. ISM

When R_{ij} is a positive number and greater than the threshold value, $a_{ij} = 1$ and $a_{ji} = 0$ is the adjacency value of x_i to x_j ($i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, n$); otherwise, $a_{ij} = 0$ and $a_{ji} = 1$. The adjacency matrix is as follows.

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & a_{12} & \ldots & a_{1n-1} & a_{1n} \\ a_{21} & a_{22} & \ldots & a_{2n-1} & a_{2n} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ a_{n1} & a_{n2} & \ldots & a_{n-1n-1} & a_{nn} \end{bmatrix}_{n\times n.} \tag{5}$$

Let

$$\boldsymbol{E} = \begin{bmatrix} 1 & 0 & \ldots & 0 & 0 \\ 0 & 1 & \ldots & 0 & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & \ldots & 0 & 1 \end{bmatrix}_{n\times n} \tag{6}$$

be a $n \times n$ identity matrix, and we have

$$\boldsymbol{A}+\boldsymbol{E} = (\boldsymbol{A}+\boldsymbol{E})^2 = \ldots = (\boldsymbol{A}+\boldsymbol{E})^{n-1} = (\boldsymbol{A}+\boldsymbol{E})^n \tag{7}$$

where $\boldsymbol{R} = (\boldsymbol{A}+\boldsymbol{E})^{n-1}$ is the reachability matrix of adjacency matrix $\boldsymbol{A}$.

$$\boldsymbol{R} = \begin{bmatrix} R_{11} & R_{12} & \ldots & R_{1n-1} & R_{1n} \\ R_{21} & R_{22} & \ldots & R_{2n-1} & R_{2n} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ R_{n1} & R_{n2} & \ldots & R_{n-1n-1} & R_{nn} \end{bmatrix}_{n\times n.} \tag{8}$$

Definition 1. In the ith row $\boldsymbol{R}_i$ ($i = 1, 2, \ldots, n$) of reachability matrix $\boldsymbol{R}$, if $R_{ij} = 1$ ($j = 1, 2, \ldots, n$), then element R_{ij} is added into the reachable set, expressed as $\boldsymbol{S}_i$.

Definition 2. In the jth column $\boldsymbol{R}_i$ ($j = 1, 2, \ldots, n$) of matrix $\boldsymbol{R}$, if $R_{ij} = 1$ ($i = 1, 2, \ldots, n$), then element R_{ij} is added into the first set, expressed as $\boldsymbol{B}_j$.

The influencing factors can be stratified based on $\boldsymbol{S}_j \cap \boldsymbol{B}_j = \boldsymbol{S}_j$, and then the highest level of factors L_1 is identified. The column and row corresponding to L_1 are removed from matrix $\boldsymbol{R}$. By the same decision rules, $L_2, L_3, \ldots, L_k$ can be identified. The last step is to establish the hierarchy model of ISM using each level of L.

2.3. The ISM based on partial correlation coefficient

The ISM based on partial correlation coefficient is described as follows.

Step 1: Obtain the correlation coefficient matrix $\boldsymbol{r}$ using Eqs. (1) and (2).
Step 2: Establish the partial correlation coefficient matrix using the inverse matrix of r from Eqs. (3) and (4).

Step 3: Transform adjacency matrix $\boldsymbol{A}$ using Eq. (5), which is made of correlation coefficient thresholds to reachability matrix $\boldsymbol{R}$ using Eq. (7).
Step 4: Get the advanced set and the reachable set of matrix $\boldsymbol{R}$, and obtain the first level of elements by the definition of ISM.
Step 5: In the reachability matrix $\boldsymbol{R}$, remove the corresponding row and column of the elements in the first level, then rebuild the reachability matrix, and run back to Step 5, the loop will not stop until no element is in reachability matrix.
Step 6: Build ISM based on the elements from each level.

3. ISM Analysis for Ethylene Production

Seven common process technologies in Chinese ethylene industries are shown in Table 2 [13]. In this study, the Lummus order separation technology is taken as an example to illustrate the effectiveness of proposed method.

Table 2
Ethylene production process

Technology	Descriptions
I	S&W front-end depropanization and front adding hydrogen technology
II	Lummus order separation technology
III	TPL patent technology
IV	Mitsubishi heavy industries front-end depropanization and behind adding hydrogen
V	Dalian University technology
VI	Linde front-end deethanization technology
VII	KBR front-end depropanization and front adding hydrogen technology

Ethylene production can be divided into two parts: cracking and separation. A large amount of fuel is needed to provide heat to the tube cracking reactions and a transfer line exchanger produces a great amount of steam by recovering the waste heat. To make the raw material hydrocarbon complete the cracking reactions in a short time and reduce the coke simultaneously, steam should be injected when the hydrocarbon is fed into the cracking furnace. The separation section mainly contains three parts: rapid cooling, compression, and separation. The main energy consumption is the power of compressor, heat supply in separation such as by steam, and cooling of compressor and cold box. A typical framework of a sequential separation process is shown in Fig. 1.

3.1. Factor analysis on energy efficiency in ethylene plant

The energy consumption cost may be up to more than 50% of the total cost for ethylene production process. The factors affecting the overall energy consumption involve the quality of raw material, cracking technology, separation process, and supporting facilities [4]. More than 70% of the total cost in ethylene production is taken by cracking materials (naphtha, light diesel oil, raffinate, hydrogenation tail oil, carbon 3, carbon 4, carbon 5 and other materials). The main energy types in the ethylene utilization [13] are as follows: the water including recycled water, industrial water and boiler feed water; the power (electricity); steams including those at ultra-high pressure, high pressure, medium pressure, and low pressure; fuels including fuel gas, light and heavy oils; N_2 and compressing air. Because the consumption of N_2 and compressing air is low, they are not considered in energy efficiency of ethylene production process.

3.2. Regular operation data acquisition and data pretreatment

Based on the analysis of energy consumption in the ethylene plant, the energy data are collected in actual production monthly, including several crudes (naphtha, light diesel oil, raffinate, hydrogenation tail oil, carbon 3–5, *etc.*), ethylene scheme, yield of ethylene, propylene yield, total yield; fuel gas (fuelgas), light oil (lightoil) and heavy oil (heavyoil); ultra-high pressure steam (superhp), high pressure steam (highpress), medium pressure steam (middlepress), low pressure steam (lowpress); recycled water (circlew), industrial water (industryw), boiler feed water (boilerw); electricity.

Process operation data are in complicated non-linear time series, including noise, outliers, inconsistent values and so on. The units of variable are different, and the values are incomparable, so the consistency should be checked [11]. A normalized process or data transformation is necessary before the ISM is established. For an ethylene process, short data length leads to misjudgment [12]. When the data length is sufficiently long, Grubbs' criterion can be applied to test the consistency [29]. The criterion is: x_i is rejected if $T \geq T(n, \alpha)$, where, n is sample size, α stands for the significance level, the critical value of $T(n, \alpha)$ can be found in reference [29], and

$$T = \frac{|V|}{S} = \frac{|x_i - \bar{x}|}{S} \tag{9}$$

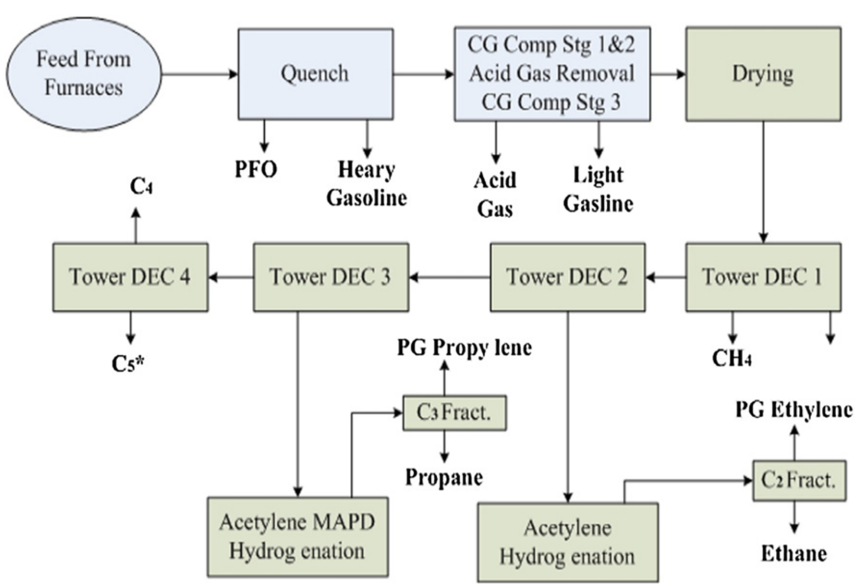

Fig. 1. A typical framework of a sequential separation process.

where $\overline{x_j(k)} = \frac{1}{N}\sum_{i=1}^{N} x_{ij}(k)$ and $S_j(k) = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(x_{ij}(k)-\overline{x_j(k)}\right)^2}$ ($j = 1, 2, \ldots, n$; $k = 1, 2, \ldots, N$).

We adopt a general method to evaluate the energy consumption in ethylene plant according to the calculation method of SH/T3110-2001 [30]. The energy data of fuel, steam, water and electricity are converted to unit GJ. According to the feature of paraffin hydrocarbon, olefin, naphthenic hydrocarbon, aromatic hydrocarbon (PONA), the crude oils are transformed to PONA values. Because the PONA value can reflect cracking features for oils, avoid the null value of oil condition, and help substitute excessive raw material oil input with single PONA value to reduce the evaluation index.

The method of proportion conversion is often used in data normalization. Some variables have positive effects on the subject and the following conversion is used

$$x'_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}}. \tag{10}$$

Some variables have negative effects on the subject and the conversion is

$$x'_{ij} = 1 - \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}} = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}} \tag{11}$$

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

3.3. Analysis of ethylene plant consumption based on ISM model

Fig. 2 gives the analysis process of ISM for energy consumption in an ethylene plant. The energy consumption evaluation algorithm is as follow.

Step 1: With the data from different techniques or from different scales and consistency checking, PONA value and normalization are obtained with Eqs. (9)–(11).

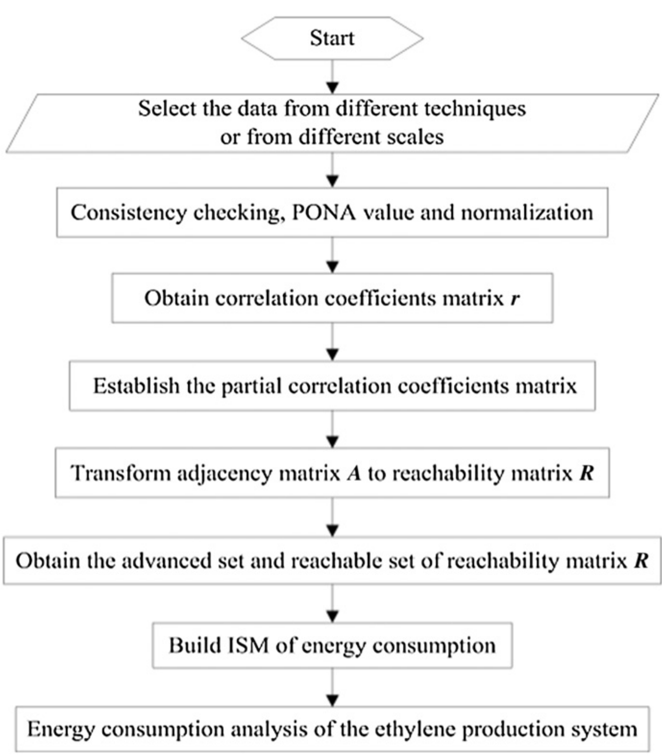

Fig. 2. ISM process of energy consumption for the ethylene production system.

Step 2: Obtain correlation coefficient matrix $\boldsymbol{r}$ using Eq. (2) for energy consumption based on Eq. (1).

Step 3: Establish the partial correlation coefficient matrix using the inverse matrix of $\boldsymbol{r}$ from Eqs. (3) and (4).

Step 4: Transform adjacency matrix $\boldsymbol{A}$ using Eq. (5), which is made of correlation coefficient thresholds of energy consumption to reachability matrix $\boldsymbol{R}$ using Eq. (7).

Step 5: Obtain the advanced set and reachable set of reachability matrix $\boldsymbol{R}$, and the first level of elements can be obtained by the definition of ISM.

Step 6: In the reachability matrix $\boldsymbol{R}$, remove the corresponding row and column of elements in the first level, and then rebuild the reachability matrix, run back to Step 5, the loop will not stop until no element is in the reachability matrix.

Step 7: Build ISM of energy consumption based on the elements from each level.

4. Case Study: Energy Consumption Analysis for Ethylene Production

4.1. Energy consumption of ethylene order separation technology

The ethylene order separation technology (class II) is taken as an example to illustrate the proposed method. Nine ethylene plants in China supply monthly data on energy consumption in nearly ten years, containing raw materials (light diesel oil, naphtha, raffinate hydrogenation tail oil, light hydrocarbons, C_3, C_4, C_5, *etc.*), water (industrial water, recycled water, boiler water), electricity, fuel (fuel gas, light and heavy oils), and steam (ultra-high pressure, high pressure, medium pressure, low pressure). Because the number of data is huge, only monthly data from one of the ethylene plants in 2010 are shown for the order separation approach. Fig. 3 shows the raw materials, Fig. 4 shows the required water, and Fig. 5 shows the required fuel, steam and electricity.

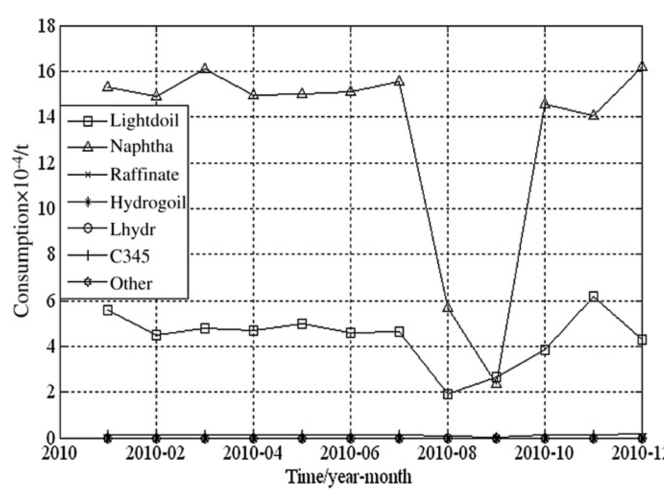

Fig. 3. The raw materials of one ethylene plant in 2010.

Most ethylene plants usually use the special energy consummation (SEC) as the energy efficiency index, which is that needed for producing one ton ethylene, GJ per ton of ethylene, and reflects the energy consumption level to some extent [13]. The annual energy consumption of the order separation approach is obtained with the method in literature [12], as shown in Fig. 6. The overall SEC presents a downward trend between 2001 and 2010, and the range of SEC is 27.36–32.81 GJ per ton of ethylene. SEC ranges from 27.36 to 29.7 GJ per ton of ethylene since 2005, while the average industrial naphtha cracking energy consumption is about 26–31 GJ per ton of ethylene around the world in 2006 [3].

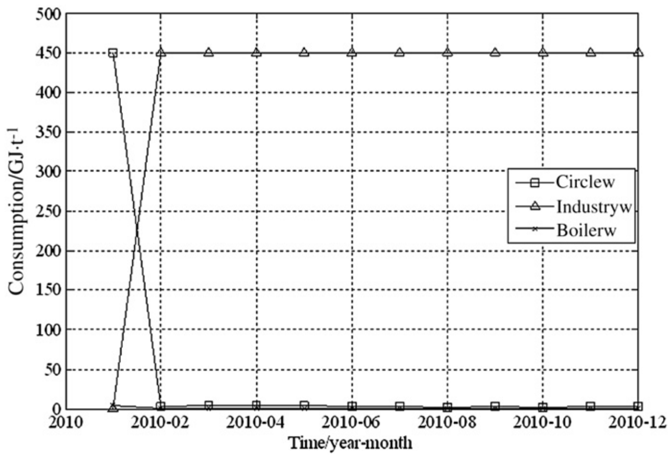

Fig. 4. The required water of one ethylene plant in 2010.

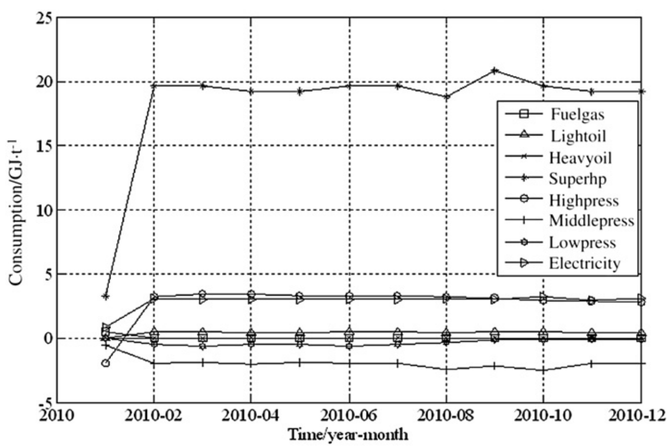

Fig. 5. The required fuel, steam and electricity of one ethylene plant in 2010.

4.2. Energy consumption analysis of ethylene order separation

First, the monthly data from nine ethylene plants are taken to analyze the energy consumption of ethylene plant with the order separation technology, and the consistency test is used to remove outliers according to Eq. (8). Second, the PONA value and normalization are used to obtain consistent unit, then obtain the energy consumption data by different scales and different techniques. According to Eqs. (1) and (2), the correlation matrix of ethylene order separation technology can be obtained, as shown in Table 3. According to Eqs. (3) and (4), the partial correlation matrix is obtained and shown in Table 4.

If correlation coefficients are obtained by energy-related materials of ethylene production, such as raw materials, water, steam, electricity, fuel, and utilities, is greater than 0.3, then they are related. To analyze the effect of ethylene productivity, if the correlation coefficient is not less than 0.4, the value between two variables in the adjacency matrix is 1. If $R_{ij} \geq 0.4$, then $a_{ij} = 1$ and $a_{ji} = 0$; if $R_{ij} \leq -0.4$, called negative correlation, $a_{ij} = 0$ and $a_{ji} = 1$.

Reachability matrix $\boldsymbol{R}$ is given in Table 5, by the analysis thresholds of related elements with Eqs. (5)–(7). The first reachability matrix of the energy consumption includes all elements. Low pressure steam affects fuel gas, medium-pressure steam affects ultra-high pressure steam, heavy oil affects boiler water and high-pressure steam affects ultra-high pressure steam, boiler water and electricity.

The first set $\boldsymbol{B}_j$, reachable set $\boldsymbol{S}_i$, and their intersection $\boldsymbol{S}_i \cap \boldsymbol{B}_j$ in the first level can be obtained by the reachability matrix $\boldsymbol{R}$. The ISM is shown in Table 6.

In Table 6, the elements affecting the ethylene plant energy consumption in the first level can be obtained and the entries in the first level of reachability matrix $\boldsymbol{R}$ are removed. The elements at each level can be obtained and the ISM is built, as shown in Fig. 7. ISM approach can transform the multivariate problem of ethylene plant into several sub-variable problems so that the multi-level hierarchical structure model of the energy consumption can be built, with which the complex industrial structure can be analyzed in a more efficient way. The main significant factors affecting the energy efficiency of ethylene order separation technology are PONA (raw materials), light oil, ultra-high pressure steam, recycled water, industrial water, boiler water, and electricity. The second layer factors, such as heavy oil, medium-pressure and low pressure steams, are affected by the first-level element of the crude oil, water and electricity. They not only play a linkage role in the energy efficiency, but also affect the high-pressure steam.

Similarly, the ISM of S&W front-end depropanization and front adding hydrogen technologies (class II) is obtained, as shown in Fig. 8. The main significant factors affecting the energy efficiency of class I are PONA (raw materials), heavy oil, ultra-high pressure steam, recycled water, industrial water, boiler water, and electricity. The PONA, fuel gas, water, and electricity are all primary factors influencing the energy

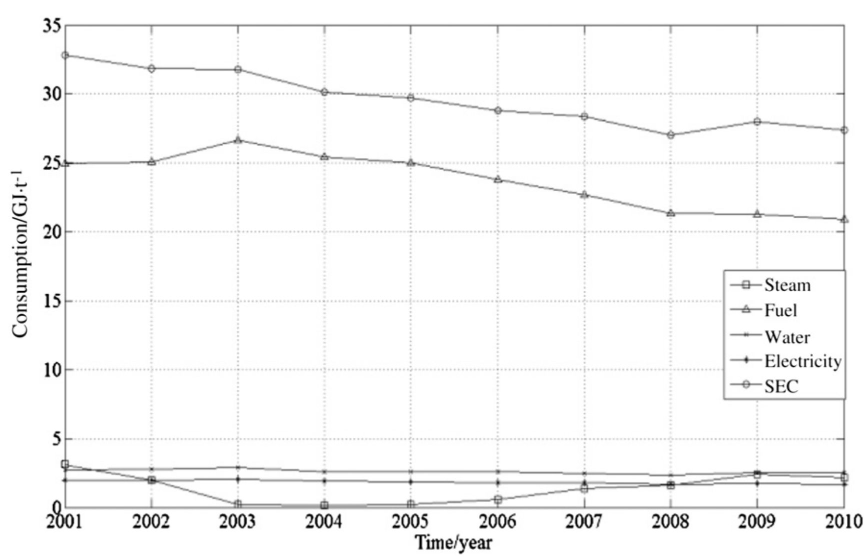

Fig. 6. The annual energy consumption of order separation approach (recent 10 years).

Table 3
The correlation matrix of the energy consumption data

	PONA	Fuelgas	Lightoil	Heavyoil	Superhp	Highpress	Middlepress	Lowpress	Circlew	Industryw	Boilerw	Electricity
PONA	1.000	0.046	0.281	−0.049	0.351	−0.354	−0.069	0.245	−0.012	−0.033	0.090	−0.446
Fuelgas	0.046	1.000	−0.407	0.491	−0.239	−0.145	−0.334	−0.636	0.064	0.015	0.231	0.341
Lightoil	0.281	−0.407	1.000	−0.197	0.313	−0.177	0.028	0.152	−0.141	−0.060	0.011	−0.469
Heavyoil	−0.049	0.491	−0.197	1.000	0.112	−0.458	−0.282	−0.605	−0.200	−0.032	0.771	0.170
Superhp	0.351	−0.239	0.313	0.112	1.000	−0.695	−0.247	0.331	0.075	−0.070	0.221	−0.733
Highpress	−0.354	−0.145	−0.177	−0.458	−0.695	1.000	0.097	−0.031	−0.039	0.015	−0.489	0.568
Middlepress	−0.069	−0.334	0.028	−0.282	−0.247	0.097	1.000	0.294	0.254	0.121	−0.081	0.105
Lowpress	0.245	−0.636	0.152	−0.605	0.331	−0.031	0.294	1.000	0.139	0.021	−0.405	−0.427
Circlew	−0.012	0.064	−0.141	−0.200	0.075	−0.039	0.254	0.139	1.000	0.001	−0.118	0.108
Industryw	−0.033	0.015	−0.060	−0.032	−0.070	0.015	0.121	0.021	0.001	1.000	−0.047	0.058
Boilerw	0.090	0.231	0.011	0.771	0.221	−0.489	−0.081	−0.405	−0.118	−0.047	1.000	0.004
Electricity	−0.446	0.341	−0.469	0.170	−0.733	0.568	0.105	−0.427	0.108	0.058	0.004	1.000

Table 4
The partial correlation matrix of the energy consumption data

	PONA	Fuelgas	Lightoil	Heavyoil	Superhp	Highpress	Middlepress	Lowpress	Circlew	Industryw	Boilerw	Electricity
PONA	−1.000	0.386	0.253	−0.080	0.013	0.016	0.003	0.311	−0.045	−0.012	0.185	−0.182
Fuelgas	0.386	−1.000	−0.386	0.049	−0.313	−0.402	−0.348	−0.485	0.222	0.029	−0.197	0.118
Lightoil	0.253	−0.386	−1.000	−0.214	0.005	−0.119	−0.015	−0.379	−0.083	−0.030	0.065	−0.138
Heavyoil	−0.080	0.049	−0.214	−1.000	0.113	−0.409	−0.144	−0.319	−0.318	−0.021	0.574	0.337
Superhp	0.013	−0.313	0.005	0.113	−1.000	−0.401	−0.493	0.180	0.355	0.004	0.060	−0.363
Highpress	0.016	−0.402	−0.119	−0.409	−0.401	−1.000	−0.344	−0.193	−0.106	−0.048	−0.093	0.436
Middlepress	0.003	−0.348	−0.015	−0.144	−0.493	−0.344	−1.000	0.133	0.293	0.103	0.177	0.065
Lowpress	0.311	−0.485	−0.379	−0.319	0.180	−0.193	0.133	−1.000	−0.028	0.004	−0.153	0.044
Circlew	−0.045	0.222	−0.083	−0.318	0.355	−0.106	0.293	−0.028	−1.000	−0.063	0.039	0.330
Industryw	−0.012	0.029	−0.030	−0.021	0.004	−0.048	0.103	0.004	−0.063	−1.000	−0.040	0.043
Boilerw	0.185	−0.197	0.065	0.574	0.060	−0.093	0.177	−0.153	0.039	−0.040	−1.000	0.053
Electricity	−0.182	0.118	−0.138	0.337	−0.363	0.436	0.065	0.044	0.330	0.043	0.053	−1.000

Table 5
The reachability matrix of the energy consumption data

	PONA	Fuelgas	Lightoil	Heavyoil	Superhp	Highpress	Middlepress	Lowpress	Circlew	Industryw	Boilerw	Electricity
PONA	1	0	0	0	0	0	0	0	0	0	0	0
Fuelgas	0	1	0	0	0	0	0	0	0	0	0	0
Lightoil	0	0	1	0	0	0	0	0	0	0	0	0
Heavyoil	0	0	0	1	0	0	0	0	0	0	1	0
Superhp	0	0	0	0	1	0	0	0	0	0	0	0
Highpress	0	1	0	1	1	1	0	0	0	0	1	1
Middlepress	0	0	0	0	1	0	1	0	0	0	0	0
Lowpress	0	1	0	0	0	0	0	1	0	0	0	0
Circlew	0	0	0	0	0	0	0	0	1	0	0	0
Industryw	0	0	0	0	0	0	0	0	0	1	0	0
Boilerw	0	0	0	0	0	0	0	0	0	0	1	0
Electricity	0	0	0	0	0	0	0	0	0	0	0	1

Table 6
The ISM model of the energy consumption data

Variables	Reachable sets	First set	Intersection
PONA	PONA	PONA	PONA
Fuelgas	Fuelgas	Fuelgas, highpress, lowpress	Fuelgas
Lightoil	Lightoil	Lightoil	Lightoil
Heavyoil	Heavyoil, boilerw	Heavyoil, highpress	Heavyoil
Superhp	Superhp	Superhp, highpress, middlepress	Superhp
Highpress	Fuelgas, heavyoil, superhp, highpress, boilerw, electricity	Highpress	Highpress
Middlepress	Superhp, middlepress	Middlepress	Middlepress
Lowpress	Fuelgas, lowpress	Lowpress	Lowpress
Circlew	Circlew	Circlew	Circlew
Industryw	Industry	Industryw	Industry
Boilerw	Boiler	Heavyoil, highpress, boilerw	Boiler
Electricity	Electricity	Highpress, electricity	Electricity

efficiency in the two technologies. However, we should pay attention to the heavy oil in class I and light oil in class II, because their levels are different in different technologies.

Since PONA, fuel gas, water, and electricity influence the energy efficiency in an ethylene plant, so the energy efficiency may be very different when their quantity or quality is different. The ultra-high pressure

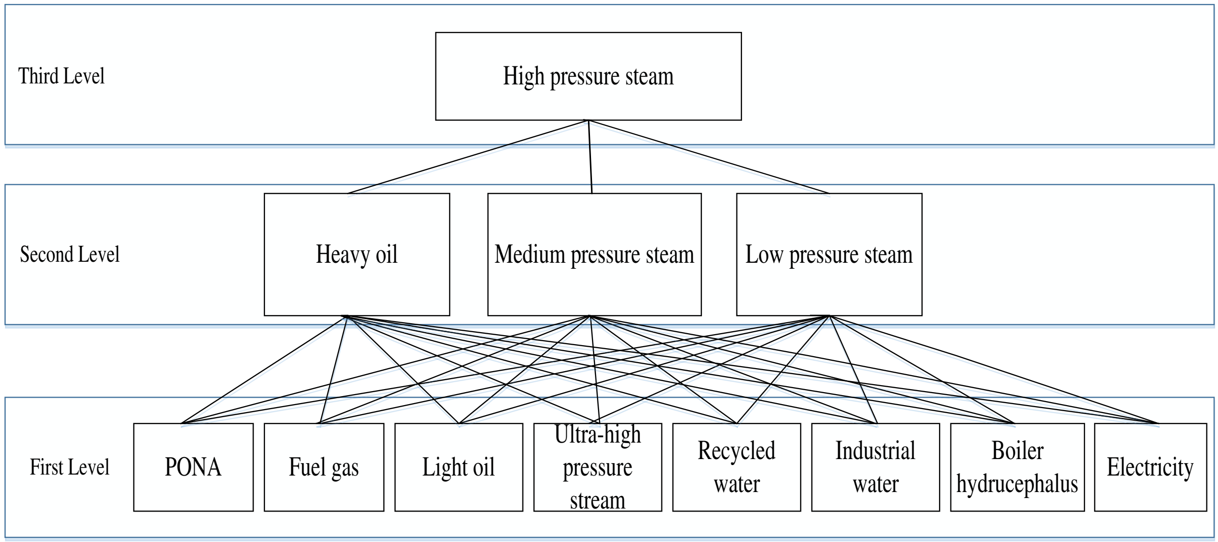

Fig. 7. The cause–effect of energy consumption of II class based on ISM model.

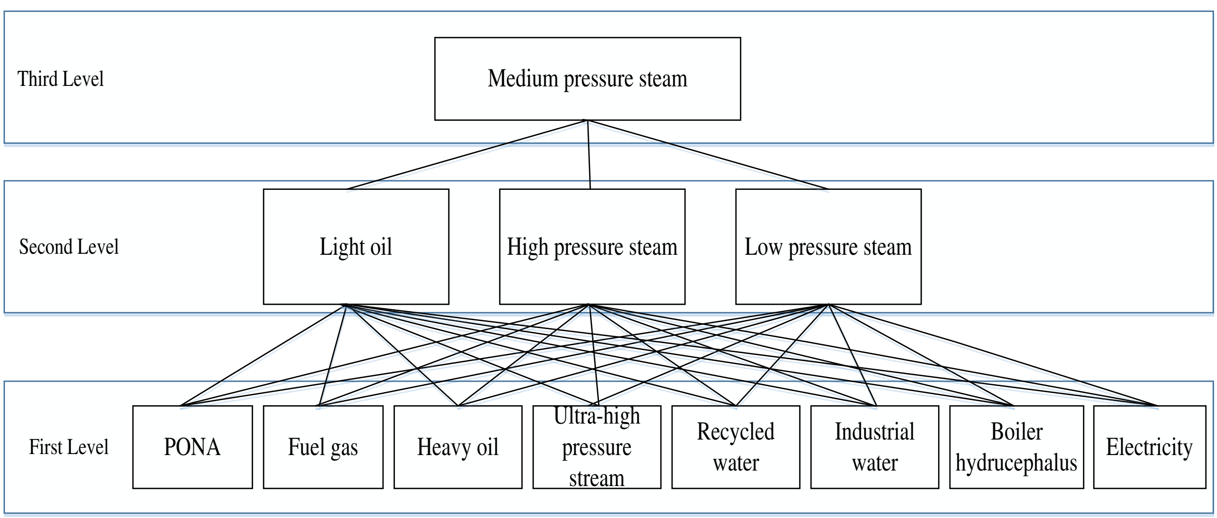

Fig. 8. The cause–effect of energy consumption of class I based on ISM model.

steam should take the first place because it affects the energy efficiency significantly, and the high-pressure steam is the basic factor for improvement of energy efficiency. Moreover, the light oil and the heavy oil in the ISM are at different levels, so they influence with each other. In order to improve the energy efficiency in an ethylene production system, appropriate PONA, fuel gas, water, electricity and raw materials should be applied. Actually, the order separating process is to transform crude naphtha to mixed oil first, then increase oil PONA value, that is, enhance the mass fraction of hydrogen and lower aromatic mass fraction. Reducing the medium pressure steam of demethanizer tower can further reduce the energy consumption and improve the yield of ethylene. Catalytic distillation and segregation shunt can use water resources cyclically, which is the improvement by Sinopec and other ethylene plants from 2008 to 2010 [1,13,31].

The PONA value in the first lever and the middle pressure steam consumption in the second lever from one ethylene plant in ten years are used to evaluate the proposed method with the order separation approach, as shown in Fig. 9. Comparing data of year 2005 with that of 2010, we see that the PONA value of raw material oil increases from 3.2 to 3.46 per ton of ethylene and the medium pressure steam

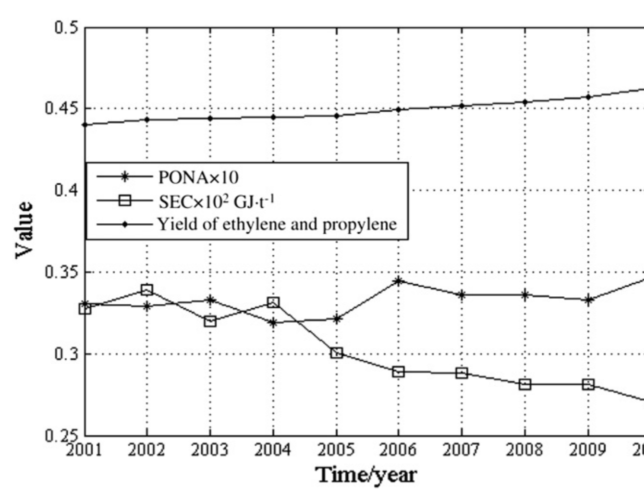

Fig. 9. The values of PONA, middle press steam and SEC of one ethylene plant in ten years.

consumption reduces from 0.2 to −0.6 tons per ton of ethylene, so the SEC is decreased by 10%. From 2001 to 2005, the PONA value of raw material oil is less than 3.3 per ton of ethylene, the medium pressure steam consumption exceeds 0.2 tons per ton of ethylene, and the SEC is much higher than 30.1 GJ per ton of ethylene. However, after 2006 PONA value of raw material oil increases, the medium pressure steam consumption of demethanizer tower reduces, and the SEC is in decreasing trend with time. All these improvements are accordance with the hierarchy analysis in the ISM of ethylene order separation technology.

5. Conclusions

Taking the order separation of ethylene plants as an example, the proposed ISM can be used to obtain the hierarchical structure for the energy consumption. A comparison shows that energy consumption factors by the model are consistent with those in an actual ethylene plant. Combining process knowledge and data analysis from daily operation data, as well as the conclusion from the analysis of mechanism model, the established ISM can reflect the real situation of ethylene plant energy efficiency and propose appropriate suggestions to improve energy utilities. In addition, the algorithm can be used to analyze the energy consumption of other technologies and the model can provide effective guidance to improve the operation.

In our further study, we will investigate and integrate other methods, such as data envelopment analysis and neural network, to analyze input–output energy measuring of ethylene production system. The method proposed in this study can be applied to evaluate the performance of other processes.

References

[1] D.S. Guan, W.Y. Ji, Review of Sinopec's ethylene production in 2008, *Ethylene Ind.* 21 (1) (2009) 1–6.
[2] L.J. Zhang, J. Hu, Review of Sinopec's ethylene production in 2008, *Ethylene Ind.* 21 (1) (2009) 7–10.
[3] T. Ren, M. Patel, M. Blok, Olefins from conventional and heavy feedstocks: Energy use in steam cracking and alternative processes, *Energy* 31 (2006) 425–451.
[4] D.R. Wu, K. He, H.F. Zhu, Analysis of energy consumption and energy saving technology in ethylene complex, *Chem. Eng. (China)* 35 (2007) 66–71.
[5] L.J. Zhang, Application of energy conservation and emission reduction techniques in ethylene plants, *Sino-Global Energy* 14 (2009) 90–94.
[6] G.G. Li, X. He, Z.H. Sheng, Technology analysis and energy saving of ethylene plant, *Petrochem. Technol.* 38 (2009) 115–123.
[7] C.S. Yang, The design of quenching oil system for ethylene plants and technical revamping aimed at raising energy efficiency, *Sino-global Energy* 16 (2011) 106–111.
[8] J. Buehler, N. Genty, A successful approach to improve energy utilization in ethylene units, Ethylene producer conference Houston, USA, 2007.
[9] K. Hirata, Energy saving for ethylene process by advanced process integration, *Chem. Eng. Trans.* 25 (2011) 81–86.
[10] W.Q. Tang, Techno-economic assessment on ethylene fragmentation plant with light hydrocarbon as raw material, *Techno-Econ. Petrochem.* 5 (2004) 19–23.
[11] Q.X. Zhu, X.Y. Shi, X.B. Gu, Q. Tian, Time-series data fusion and its application to energy efficiency value for ethylene plants, *J. Chem. Ind. Eng. (China)* 61 (2010) 2620–2626.
[12] Z.Q. Geng, X.Y. Shi, X.B. Gu, Q.X. Zhu, Hierarchical linear optimal fusion algorithm and its application in ethylene energy consumption indices acquisition, *J. Chem. Ind. Eng. (China)* 61 (2010) 2056–2060.
[13] Z.Q. Geng, Y.M. Han, X.B. Gu, Q.X. Zhu, Energy efficiency estimation based on data fusion strategy: Case study of ethylene product industry, *Ind. Eng. Chem. Res.* 51 (2012) 8526–8534.
[14] J. Fu, Q. Xu, Simultaneous study on energy consumption and emission generation for an ethylene plant under different start-up strategies, *Comput. Chem. Eng.* 56 (2013) 68–79.
[15] C. Liu, Q. Xu, Emission source characterization for proactive flare mini-mization during ethylene plant start-ups, *Ind. Eng. Chem. Res.* 49 (2010) 5734–5741.
[16] J.N. Warfield, Binary matrices in system modeling, *IEEE Trans. Syst. Man Cybern.* 3 (5) (1973) 441–449.
[17] T.C. Kuo, H.Y. Ma, S.H. Huang, A.H. Hu, C.S. Huang, Barrier analysis for product service system using interpretive structural model, *Int. J. Adv. Manuf. Technol.* 49 (4) (2010) 407–417.
[18] M.N. Faisal, Analyzing the barriers to corporate social responsibility in supply chains: An interpretive structural modelling approach, *Int. J. Logist. Res. Appl.* 13 (3) (2010) 179–195.
[19] F. Talib, Z. Rahman, M.N. Qureshi, Analysis of interaction among the barriers to total quality management implementation using interpretive structural modeling approach, *Benchmarking Int. J.* 18 (4) (2011) 563–587.
[20] S. Chandramowli, M. Transue, F.A. Felder, Analysis of barriers to development in landfill communities using interpretive structural modeling, *Habitat Int.* 35 (2) (2011) 246–253.
[21] K. Govindan, M. Palaniappan, Q. Zhu, D. Kannan, Analysis of third party reverse logistics provider using interpretive structural modeling, *Int. J. Prod. Econ.* 140 (1) (2012) 204–211.
[22] N.L. Yu, D.Y. Yi, X.Q. Tu, Analyze auto-correlations and partial-correlations function in time series, *Math. Theory Appl.* 27 (1) (2007) 54–57.
[23] A. Vargha, L.R. Bergman, H.D. Delaney, Interpretation problems of the partial correlation with nonnormally distributed variables, *Qual. Quant.* (2011) 1–12.
[24] Y. Fan, L.S. Sirish, D.Y. Xiao, Signed directed graph modeling of industrial processes and their validation by data-based methods, 2010 Conference on Control and Fault Tolerant Systems 2010, pp. 387–392.
[25] R. Hildebrand, M. Gevers, G. Solari, Closed-loop optimal experiment design: The partial correlation approach, 49th IEEE Conference on Decision and Control (CDC), IEEE 2010, pp. 2855–2862.
[26] W. Bergsma, A Note on the Distribution of the Partial Correlation Coefficient With Nonparametrically Estimated Marginal RegressionsarXiv, preprint arXiv:1101.4616 2011.
[27] J.-M. Kim, Y.-S. Jung, C. Taeryon, A.S. Engin, Partial correlation with copula modeling, *Comput. Stat. Data Anal.* 55 (2011) 1357–1366.
[28] W. Hopkins, A new view of statistics, http://www.sportsci.org/resource/stats/2002-08-21.
[29] H. Zhang, T.S. Tong, F. Zhang, H.L. Liu, Consensus measurement in micro-inertial sensors, *J. Transducer Technol.* 10 (2001) 40–41.
[30] Calculation Method for Energy Consumption in Petrochemical Engineering Design SH/T 3110, 2011.
[31] X.L. Wang, The dynamic benchmarking method for energy consumption of ethylene production process, *Comput. Appl. Chem.* 27 (9) (2010) 1166–1170.