



# Key factors identification and dynamic fuzzy assessment of health, safety and environment performance in petroleum enterprises

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## ARTICLE INFO

### Article history:

Received 8 July 2016

Received in revised form 14 December 2016

Accepted 27 December 2016

### Keywords:

HSE

Key performance factor identification

Performance assessment

Dynamic fuzzy comprehensive evaluation

Correlation analysis

## ABSTRACT

Performance evaluation of Health, Safety and Environment (HSE) in large petroleum corporation is an indispensable way of strengthening safety management and promoting continuous improvement. It is also a tool for petroleum enterprises to measure their HSE performance levels. As HSE has been applied in petrochemical fields for decades, it is always time-consuming to assess HSE performance because there are so many evaluation indicators. In order to evaluate HSE performance efficiently, Spearman's correlation coefficient method is applied to identify the key HSE performance factors based on historical data for the first time. Besides, conventional scoring method is too cursory and arbitrary by simply grading according to total scores of all indicators. An improved fuzzy comprehensive evaluation method is proposed to address this problem, as well as improve the predictability of HSE performance trends based on dynamic fuzzy theory. Finally, the HSE performance evaluation of gas transmission field is chosen as a case to illustrate the effectiveness of the method and a comparison with traditional fuzzy comprehensive evaluation method is made.

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## 1. Introduction

Health, Safety and Environment, usually referred to as HSE, is a systematic and integrative management system developed in the 1980s. In the petrochemical industries, it aims to assure safe production, reduce risks, prevent accidents and achieve sustainable development (Petroleum Safety Authority Norway, 2016). The principal of HSE is now well recognized in most petrochemical plants for its good performance (Høivik et al., 2009). Since International Organization for Standardization (ISO) began working on the formulation and development of HSE standards and systems, including ISO-9000 (ISO, 1994, 2000), ISO14001 (ISO, 1996, 2004), etc., HSE implementation has been prioritized either by both government and companies. For example, Norway's government

emphasized the importance of HSE in petroleum industries. Also Chinese government promulgated some HSE standards (e.g. GB/T 24001-1996, GB/T 28001-2001, Q/SY1002.1-2007, Q/SY1002.2-2008, etc.) to enforce health, safety and environment management in high risk industries (Liu, 2009). Especially in process industries like petrochemical companies, health, safety and environment are of prime importance. For example, Chinese major petroleum enterprises have implemented HSE management system and emphasize HSE management as an important part of enterprise safety management (Zheng et al., 2006). In some European Union (EU) member states, HSE management programs have also been developed to improve their safety performance (Duijm et al., 2008). All these studies and applications have proved that HSE system is an effective tool to enforce safety management.

Initially, most efforts were put on developing or improving HSE standards and guidelines (Redinger and Levine, 1998; Robson et al., 2007). Nowadays, more attention has been given to the performance measurement methods of HSE effectiveness (Azadeh et al., 2008, 2012; Chin et al., 2003). In spite of these efforts which have been put on HSE performance management systems; there has not been any agreed standard tool for HSE performance measurement is available (Mohammadfam et al., 2012; Gholami et al., 2015). One of the most used methods to evaluate HSE performance is indexing method, which quantifies HSE indices with defined criteria (Malmadi et al., 2010). This is also called normative method.

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Conventional normative methods are to grade a company's HSE performance by adding scores of all HSE indicators. However, with the widespread attention and use of HSE performance assessment, issues begin to emerge.

- (1) There are so many HSE performance indicators which are defined by experts (e.g. 28 indicators were defined in China National Petroleum Corporation). It requires much more resources to evaluate each fixed indicator without identifying key performance variables. Besides, according to the Pareto principle, also called the 80/20 rule, only 20% elements have significant impacts on HSE performance compared with the other 80% elements. For example, Podgórski (2015) selected 20 key performance indicators from 109 pro-active safety performance indicators with Analytic Hierarchy Process (AHP) to measure OSHMS (Occupational Safety and Health Management System) operational performance. Therefore, it is of vital importance to develop methods to identify essential performance indicators. Fortunately with the data collected from the past several decades, this issue can be addressed with statistical methods.
- (2) Conventional HSE performance evaluation result is a specific value or rank. If an evaluation result is close to the boundary of two levels, for example the value is 0.49 (assuming that value less than 0.5 is at a bad level and more than 0.5 at a good level), it is too absolute and arbitrary if we conclude it at a bad level. Many fuzzy related methods have been proposed to address boundary issues (Hsiao and Ko, 2013; Guo et al., 2009; Azadeh et al., 2013). Fuzzy comprehensive evaluation (FCE) is one of them, which use membership to represent HSE performance level (Li et al., 2015).
- (3) Determining performance level is not enough to measure HSE performance thoroughly and fairly. Imagine two company's HSE performances are both at good level, but one has the inclination toward a higher level while the other toward a lower level. Can we simply conclude that they are in the same level? Apparently the answer is no. In this paper, HSE performance level membership and development tendency will be obtained by introducing dynamic fuzzy set theory into traditional fuzzy comprehensive evaluation (FCE).

With more and more data being available, statistical methods could play a vital role in HSE performance evaluation. Spearman's rank correlation coefficient will be used to identify key performance indicators based on statistical data in this paper. It should be noted that indicators of HSE performance system are diverse since different countries or different enterprises can design their own criteria based on their understanding and requirements of HSE (Mahdavinejad et al., 2012; Honkasalo, 2000; Mustapha et al., 2014; Kongsvik et al., 2016). Although the HSE criteria prototype used in this research is from China National Petroleum Corporation (CNPC), and the method proposed in this research is illustrated by HSE performance evaluation of CNPC, we believe that it will be also helpful for other petroleum companies to improve their HSE performance evaluation.

## 2. Methodology

### 2.1. Spearman's rank correlation coefficient

In order to identify key performance affecting factors which contribute significantly to HSE performance, Spearman's rank correlation coefficient (Spearman, 1904) is used to measure the

correlations between HSE affecting factors and HSE performance based on statistical data. A brief description of calculation steps is as follows:

- (1) Choose a sample of historical data as observations. To conduct Spearman's rank correlation, there must be two sets of variables. In this research, the data is  $N = 10$  pairs of HSE affecting factors' scores and HSE performance scores, which will be explained in later section.
- (2) Replace the raw data by their ranks. For each pair of HSE affecting factors' scores and HSE performance scores, affecting factors' scores are ranked and marked as  $X_1, X_2, X_3, \dots, X_N$ . For HSE performance scores, the ranks are represented by  $Y_1, Y_2, Y_3, \dots, Y_N$ . The ranks should be in order from small to large.
- (3) Calculate correlation coefficient  $R_s$  with the following formula:

$$R_s = 1 - \frac{6 \sum_{i=1}^N d_i^2}{N(N^2 - 1)} \quad (1)$$

where  $d_i$  represents the difference between  $X$  and  $Y$ . As mentioned above,  $N = 10$  in our case. For each pair of HSE affecting factor' score  $X$  and HSE performance score  $Y$ ,  $d_i$  can be obtained. For example,  $d_1 = Y_1 - X_1$ ,  $d_2 = Y_2 - X_2$ ,  $d_3 = Y_3 - X_3$ , etc.

- (4) Check the distribution table for the critical value of correlation coefficient  $R'_s$  provided by Zar (1972). Part of the table is provided in Appendix A. These two sets of variables are correlative if  $R_s > R'_s$ . In this research it means that this factor is the key HSE performance affecting factor. Repeat step 2 to step 4 for every affecting factor, then all key performance factors can be chosen.

### 2.2. Dynamic fuzzy comprehensive evaluation (DFCE) method

The conventional FCE is improved by introducing dynamic fuzzy sets (DFS) theory to obtain a dynamic result. The basic principle of DFS is that for any variable  $x$ , it can be represented as  $x = (x, \bar{x})$ . In other words, any variable can be represented as a vector set. For dynamic membership function  $(\bar{x}(u), \bar{x}(\bar{u}))$ , define a mapping  $(u, \bar{u}) \rightarrow (\bar{x}(u), \bar{x}(\bar{u}))$  ( $\bar{x}(u) \in [0, 1]$ ,  $\bar{x}(\bar{u}) \in [0, 1]$ ) to represent the membership degree of  $(u, \bar{u})$  for  $(x, \bar{x})$ . The membership degree is higher if  $(\bar{x}(u), \bar{x}(\bar{u}))$  is closer to  $(1, 1)$ . Apparently, DFS can not only solve the boundary problem by membership but also reflect tendency by vector. Based on these definition, a dynamic fuzzy comprehensive evaluation method is established. The procedures are as follows:

- (1) Determine key performance affecting factor set  $U = \{u_1, u_2, \dots, u_n\}$ , where  $u_i$  represents each key performance factor obtained in Section 2.1.
- (2) Determine dynamic evaluation set  $V = \{(\bar{v}_1, \bar{v}_1), (\bar{v}_2, \bar{v}_2), \dots, (\bar{v}_j, \bar{v}_j), \dots, (\bar{v}_m, \bar{v}_m)\}$ , where  $\bar{v}_j$  represents possible evaluation result of the evaluation objects. For example, if the fuzzy language used to describe evaluation result is "bad, good, very good", then the dynamic evaluation set should be expressed as "(bad, bad), (good, good), (very good, very good)", where good represents "in good state with tendency to be bad".
- (3) Determine dynamic fuzzy relation matrix. Fuzzy relation matrix is used to describe the membership degree of every affecting factor to every possible evaluation result. For  $u_i$ , its membership degree to  $\bar{v}_j$  is  $\bar{r}_{ij}$  ( $0 \leq \bar{r}_{ij} \leq 1$ ). Then the

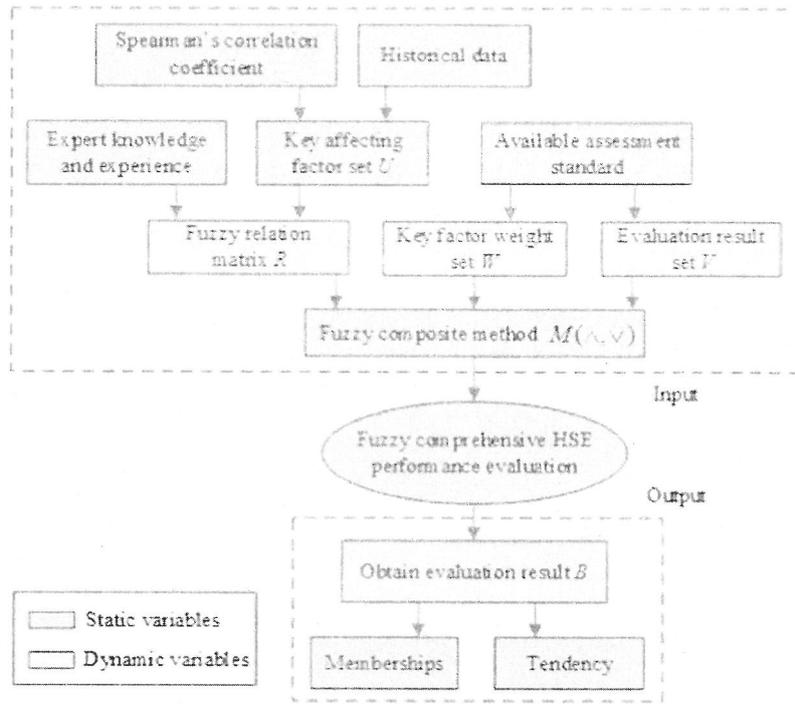


Fig. 1. Model of dynamic fuzzy comprehensive HSE performance evaluation.

membership degrees of  $u_i$  for the whole dynamic evaluation set can be described as:

$$R_i = ((\bar{r}_{i1}, \bar{r}_{i1}^-), (\bar{r}_{i2}, \bar{r}_{i2}^-), \dots, (\bar{r}_{ij}, \bar{r}_{ij}^-), \dots, (\bar{r}_{im}, \bar{r}_{im}^-)), \quad (i = 1, 2, \dots, n; j = 1, 2, \dots, m) \quad (2)$$

Correspondingly, for all of the  $n$  affecting factors, the dynamic fuzzy relation matrix  $R$  can be represented as:

$$R = \begin{bmatrix} (\bar{r}_{11}^-, \bar{r}_{11}^-) & (\bar{r}_{12}^-, \bar{r}_{12}^-) & \dots & (\bar{r}_{1j}^-, \bar{r}_{1j}^-) & \dots & (\bar{r}_{1m}^-, \bar{r}_{1m}^-) \\ (\bar{r}_{21}^-, \bar{r}_{21}^-) & (\bar{r}_{22}^-, \bar{r}_{22}^-) & \dots & (\bar{r}_{2j}^-, \bar{r}_{2j}^-) & \dots & (\bar{r}_{2m}^-, \bar{r}_{2m}^-) \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ (\bar{r}_{i1}^-, \bar{r}_{i1}^-) & (\bar{r}_{i2}^-, \bar{r}_{i2}^-) & \dots & (\bar{r}_{ij}^-, \bar{r}_{ij}^-) & \dots & (\bar{r}_{im}^-, \bar{r}_{im}^-) \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ (\bar{r}_{n1}^-, \bar{r}_{n1}^-) & (\bar{r}_{n2}^-, \bar{r}_{n2}^-) & \dots & (\bar{r}_{nj}^-, \bar{r}_{nj}^-) & \dots & (\bar{r}_{nm}^-, \bar{r}_{nm}^-) \end{bmatrix} \quad (3)$$

(4) Determine dynamic factor weight set. A factor weight set is composed of weights of key affecting factors for evaluation object. Usually it is determined by experts' experience and knowledge. A static factor weight set can be described as  $A = \{w_1, w_2, \dots, w_i, \dots, w_n\}$ , where  $w_i$  is called the weight of affecting factor  $u_i$ . Then the dynamic factor weight set is:

$$W = \{(\bar{w}_1, \bar{w}_1^-), (\bar{w}_2, \bar{w}_2^-), \dots, (\bar{w}_i, \bar{w}_i^-), \dots, (\bar{w}_n, \bar{w}_n^-)\} \quad (4)$$

(5) Obtain dynamic performance distribution set. It can be obtained by combining both dynamic fuzzy relation matrix and dynamic factor weight set and described as:

$$B = W \circ R = \{(\bar{w}_1, \bar{w}_1^-), (\bar{w}_2, \bar{w}_2^-), \dots, (\bar{w}_i, \bar{w}_i^-), \dots, (\bar{w}_n, \bar{w}_n^-)\} \circ$$

$$\begin{bmatrix} (\bar{r}_{11}^-, \bar{r}_{11}^-) & (\bar{r}_{12}^-, \bar{r}_{12}^-) & \dots & (\bar{r}_{1j}^-, \bar{r}_{1j}^-) & \dots & (\bar{r}_{1m}^-, \bar{r}_{1m}^-) \\ (\bar{r}_{21}^-, \bar{r}_{21}^-) & (\bar{r}_{22}^-, \bar{r}_{22}^-) & \dots & (\bar{r}_{2j}^-, \bar{r}_{2j}^-) & \dots & (\bar{r}_{2m}^-, \bar{r}_{2m}^-) \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ (\bar{r}_{i1}^-, \bar{r}_{i1}^-) & (\bar{r}_{i2}^-, \bar{r}_{i2}^-) & \dots & (\bar{r}_{ij}^-, \bar{r}_{ij}^-) & \dots & (\bar{r}_{im}^-, \bar{r}_{im}^-) \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ (\bar{r}_{n1}^-, \bar{r}_{n1}^-) & (\bar{r}_{n2}^-, \bar{r}_{n2}^-) & \dots & (\bar{r}_{nj}^-, \bar{r}_{nj}^-) & \dots & (\bar{r}_{nm}^-, \bar{r}_{nm}^-) \end{bmatrix} = \{(\bar{b}_1, \bar{b}_1^-), (\bar{b}_2, \bar{b}_2^-), \dots, (\bar{b}_j, \bar{b}_j^-), \dots, (\bar{b}_m, \bar{b}_m^-)\} \quad (5)$$

where  $\bar{b}_j$  represents the membership degree of evaluation object to evaluation classification  $\bar{v}_j$ .  $W$  is the dynamic factor weight set obtained in Eq. (4) and  $R$  is the dynamic fuzzy relation matrix obtained in Eq. (3). The performance distribution set of evaluation object can be synthesized by operator “ $\circ$ ”. The symbol “ $\circ$ ” represents fuzzy composition between weighted dynamic fuzzy relation matrix  $R$  and dynamic factor weight set  $W$ . In this research  $M(\wedge, \vee)$  model (Zadeh, 1985) is chosen for its simplicity and valid application in HSE performance evaluation. It provides dominant-factor analysis in order to select those values with a larger effect (Li et al., 2015). See Eq. (6).

$$\bar{b}_j = \bigvee_{i=1}^n (w_i \wedge r_{ij}) \quad , i = 1, 2, \dots, n; j = 1, 2, \dots, m \quad (6)$$

where “ $\wedge$ ” indicates that the smaller values are chosen from  $w_i$  and  $r_{ij}$ . “ $\vee$ ” aims to obtain the maximum value from the smaller values. Finally, normalization is conducted to  $\bar{b}_j$  for an intuitive result, see Eq. (7).

**Table 1**  
HSE performance indicators defined in *Standard* (adapted from Yan et al., 2013).

No.	HSE performance indicators	Score	Code	No.	HSE performance indicators	Score	Code
1	Leadership and Commitment	160	$n_1$	15	HSE Management of Contractor and Suppliers	90	$n_{15}$
2	Health, Safety and Environment Mission	100	$n_2$	16	Customers and Products	30	$n_{16}$
3	Hazard Identification, Risk Assessment and Determining Controls	150	$n_3$	17	Community and Public Relations	40	$n_{17}$
4	Legal and Other Requirements	40	$n_4$	18	Permit to Work	100	$n_{18}$
5	Objectives and Targets	90	$n_5$	19	Operational Control	360	$n_{19}$
6	Management Programs	40	$n_6$	20	Management of Change	60	$n_{20}$
7	Organization Approach, Obligations	90	$n_7$	21	Emergency Preparedness and Response	90	$n_{21}$
8	Superintendent Representatives	30	$n_8$	22	Performance Measurement and Monitoring	100	$n_{22}$
9	Resources	70	$n_9$	23	Evaluation of Compliance	40	$n_{23}$
10	Competence, Training and Awareness	120	$n_{10}$	24	Non-Conformance, Corrective and Preventive Action	80	$n_{24}$
11	Communication and Consultation	70	$n_{11}$	25	Incident/Accident Report, Investigation and Management	80	$n_{25}$
12	Documentation	50	$n_{12}$	26	Control of Records	50	$n_{26}$
13	Control of Documents	40	$n_{13}$	27	Internal HSE Audit	100	$n_{27}$
14	Integrity of Facilities	130	$n_{14}$	28	Management Review	120	$n_{28}$

$$B' = \left\{ \frac{(b_1, b_1), (b_2, b_2), \dots, (b_j, b_j), \dots, (b_m, b_m)}{\sum_1^m b_i} \right\} \quad (7)$$

where  $\sum_1^m b_i$  is the sum of all membership degrees.

Therefore, the flowchart of the proposed method is shown in Fig. 1.

The first step is to determine inputs, which consist of fuzzy relation matrix  $R$ , evaluation result set  $V$  and key factor weight set  $W$ . All of these inputs are characterized with dynamic performance, as stated above. Generally, the evaluation result set  $V$  and key factor weight set  $W$  are defined in HSE performance assessment standard established by HSE department of a petroleum company. And the fuzzy relation matrix  $R$  is determined by expert's judgment on every affecting factor of HSE performance. Specifically, affecting factors of HSE performance can be obtained by Spearman's correlation coefficient analysis of historical data, which constitute key affecting factor set  $U$ . After confirming  $R$ ,  $V$ , and  $W$ , fuzzy composite model  $M(\wedge, \vee)$  is used to obtain memberships to HSE performance levels.

### 3. Case of a petroleum enterprise

#### 3.1. Case introduction

The case and data used are from China National Petroleum Corporation (CNPC). In 2009, Research Institute of Safety & Environment Technology of CNPC released criteria named *HSE system performance evaluation standard* (*Standard* for short). It defined 28 HSE performance affecting factors and quantified their weights (Yan et al., 2013), shown in Table 1.

#### 3.2. Key performance indicators identification

Generally, HSE performance is scored by experts grading method. The data used in this case is from historical HSE performance factors' scores of a gas transportation field in CNPC. The total 10 sets of data are shown in Appendix B. Parameters  $N_1, N_2, \dots, N_{10}$  represent previous HSE performance evaluation results. Parameters  $n_1, n_2, \dots, n_{28}$  represent HSE performance factor respectively.  $W$  represents the overall score of HSE performance. Take factor  $n_1$  as an example to illustrate the computational process. Replace the raw data  $n_1$  and  $W$  by their ranks  $X_i$  and  $Y_i$ , as shown in the fourth and fifth columns of Table 2. Then the difference between  $X_i$  and  $Y_i$  can be determined as  $d_i$ , as shown in the six column of Table 2. Calculate Spearman's rank correlation coefficient according to Eq. (1).

According to Zar's table, the critical value is 0.564 when  $N = 10$  and  $\alpha = 0.05$ . The correlation between  $n_1$  and HSE overall performance is 0.67, which means that their relevance is high. Thus  $n_1$  can be selected as key HSE performance indicator. Similarly, other factors' coefficients of correlation can be obtained. Spearman's correlation coefficients of all affecting factors are summarized in Appendix C. According to Appendix C, it can be concluded that key HSE performance indicators are  $n_1$  (Leadership and Commitment),  $n_2$  (Health, Safety and Environment Mission),  $n_{10}$  (Competence, Training and Awareness),  $n_{13}$  (Control of Documents),  $n_{15}$  (HSE Management of Contractor and Suppliers), and  $n_{25}$  (Incident/Accident Report, Investigation and Management).

#### 3.3. Dynamic fuzzy comprehensive evaluation of HSE performance

Based on the results in Section 3.2, six key performance indicators are identified and then the affecting factor set can be

**Table 2**  
Spearman's rank correlation coefficient calculation of indicator  $n_1$ .

Ten groups ( $N = 10$ )	Previous evaluation results of indicator $n_1$	Sum of all indicators' scores $W$	Ranks of scores of $n_1$ ( $X_i$ )	Ranks of scores of $W$ ( $Y_i$ )	$d_i^2 = (Y_i - X_i)^2$	Correlation coefficient
$N_1$	75	1340	3	2	1	$R_s = 0.67$
$N_2$	82	1326	4	1	9	
$N_3$	98	1437	8	6	4	
$N_4$	90	1346	6	3	9	
$N_5$	67	1414	1	5	16	
$N_6$	71	1397	2	4	4	
$N_7$	88	1513	5	8	9	
$N_8$	96	1472	7	7	0	
$N_9$	101	1591	10	9	1	
$N_{10}$	99	1606	9	10	1	

**Table 3**  
Key performance indicator weights.

Code	Key performance factor	Score	Weight
$u_1$	Leadership and Commitment	160	0.27
$u_2$	Health, Safety and Environment Mission	100	0.17
$u_3$	Competence, Training and Awareness	120	0.20
$u_4$	Control of Document)	40	0.07
$u_5$	HSE Management of Contractor and Suppliers	90	0.15
$u_6$	Incident/Accident Report, Investigation and Management	80	0.14

represented as  $U = \{u_1, u_2, \dots, u_6\}$ . The possible evaluation results are defined in *Standard*, which is {startup level( $v_1$ ), foundation level( $v_2$ ), good level( $v_3$ ), excellent level( $v_4$ ), exceptional level( $v_5$ )}.

So the corresponding dynamic evaluation set can be expressed as

$$V = \{(\bar{v}_1, \bar{v}_1), (\bar{v}_2, \bar{v}_2), (\bar{v}_3, \bar{v}_3), (\bar{v}_4, \bar{v}_4), (\bar{v}_5, \bar{v}_5)\} \tag{8}$$

where “ $\bar{\rightarrow}$ ” represents positive trend and “ $\bar{\leftarrow}$ ” represents negative trend. For example,  $\bar{v}_4 =$  excellent level means that the HSE performance is in excellent level but its trend is undesirable.

The factor weights are determined by scores defined in *Standard*. Take For the weight of  $u_1$  for example to illustrate its computational process.

$$w_1 = 160/(160 + 100 + 120 + 40 + 90 + 80) \approx 0.27 \tag{9}$$

Table 3 shows the scores of six key performance factors and their weights.

Then the dynamic factor weight set can be expressed as

$$W = \{(\bar{w}_1, \bar{w}_1), (\bar{w}_2, \bar{w}_2), \dots, (\bar{w}_6, \bar{w}_6)\} \\ = \{(0.27, 0.27), (0.17, 0.17), (0.20, 0.20), (0.07, 0.07), (0.15, 0.15), (0.14, 0.14)\} \tag{10}$$

For every key factor, its performance level is determined by experts' voting. There are seven experts whose weights are different according to their knowledge and experience (for more details about variables defined in FCE, see (Li et al., 2015)). Voting results and experts' weights are listed in Table 4.

Then determine membership degree of every key factor to every evaluation result classification according to statistical results. Take  $u_1$  as an example to illustrate the calculation process of dynamic fuzzy relation set. In the second row of Table 4, statistical results show that both expert 6 (weight: 0.1) and expert 7 (weight: 0.1) assigned  $\bar{v}_2$  for  $u_1$ . Then the fuzzy membership of  $u_1$  for evaluation level set ( $\bar{v}_2, \bar{v}_2$ ) can be calculated as  $(r_{12}, r_{12}) = (0, 0.1 + 0.1) = (0, 0.2)$ . With the same principle,  $u_1$ 's dynamic fuzzy relation set can be calculated as:

**Table 4**  
Voting results and experts' weights.

Code	Key performance factor	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7
$u_1$	Leadership and Commitment	$\bar{v}_3$	$\bar{v}_4$	$\bar{v}_3$	$\bar{v}_3$	$\bar{v}_4$	$\bar{v}_2$	$\bar{v}_2$
$u_2$	Health, Safety and Environment Mission	$\bar{v}_4$	$\bar{v}_3$	$\bar{v}_2$	$\bar{v}_2$	$\bar{v}_4$	$\bar{v}_2$	$\bar{v}_2$
$u_3$	Competence, Training and Awareness	$\bar{v}_2$	$\bar{v}_3$	$\bar{v}_3$	$\bar{v}_3$	$\bar{v}_3$	$\bar{v}_3$	$\bar{v}_4$
$u_4$	Control of Document	$\bar{v}_4$	$\bar{v}_2$	$\bar{v}_2$	$\bar{v}_4$	$\bar{v}_3$	$\bar{v}_3$	$\bar{v}_3$
$u_5$	HSE Management of Contractor and Suppliers	$\bar{v}_2$	$\bar{v}_4$	$\bar{v}_3$	$\bar{v}_3$	$\bar{v}_3$	$\bar{v}_3$	$\bar{v}_3$
$u_6$	Incident/Accident Report, Investigation and Management	$\bar{v}_3$	$\bar{v}_2$	$\bar{v}_2$	$\bar{v}_3$	$\bar{v}_4$	$\bar{v}_4$	$\bar{v}_5$
Expert's weight		0.25	0.20	0.15	0.10	0.10	0.10	0.10

$$R_1 = \{(r_{11}, r_{11}), (r_{12}, r_{12}), (r_{13}, r_{13}), (r_{14}, r_{14}), (r_{15}, r_{15})\} \\ = \{(0, 0), (0, 0.2), (0.35, 0.15), (0.1, 0.2), (0, 0)\} \tag{11}$$

Similarly, the rest five factors' dynamic fuzzy relation sets can be obtained. The dynamic fuzzy relation matrix is shown as follows:

$$R = \begin{bmatrix} (r_{11}, r_{11}) & (r_{12}, r_{12}) & (r_{13}, r_{13}) & (r_{14}, r_{14}) & (r_{15}, r_{15}) \\ (r_{21}, r_{21}) & (r_{22}, r_{22}) & (r_{23}, r_{23}) & (r_{24}, r_{24}) & (r_{25}, r_{25}) \\ (r_{31}, r_{31}) & (r_{32}, r_{32}) & (r_{33}, r_{33}) & (r_{34}, r_{34}) & (r_{35}, r_{35}) \\ (r_{41}, r_{41}) & (r_{42}, r_{42}) & (r_{43}, r_{43}) & (r_{44}, r_{44}) & (r_{45}, r_{45}) \\ (r_{51}, r_{51}) & (r_{52}, r_{52}) & (r_{53}, r_{53}) & (r_{54}, r_{54}) & (r_{55}, r_{55}) \\ (r_{61}, r_{61}) & (r_{62}, r_{62}) & (r_{63}, r_{63}) & (r_{64}, r_{64}) & (r_{65}, r_{65}) \end{bmatrix} \\ = \begin{bmatrix} (0, 0) & (0, 0.2) & (0.35, 0.15) & (0.1, 0.2) & (0, 0) \\ (0, 0) & (0.1, 0.35) & (0, 0.2) & (0.25, 0.1) & (0, 0) \\ (0, 0) & (0, 0.25) & (0.4, 0.25) & (0.1, 0) & (0, 0) \\ (0, 0) & (0.2, 0.15) & (0.1, 0.2) & (0.25, 0.1) & (0, 0) \\ (0, 0) & (0.25, 0) & (0.35, 0.2) & (0, 0.2) & (0, 0) \\ (0, 0) & (0, 0.35) & (0.25, 0.1) & (0.1, 0.1) & (0.1, 0) \end{bmatrix} \tag{12}$$

Based on  $R$  and  $W$ , dynamic performance distribution set  $B$  can be determined according to Eq. (5).

$$B = W \circ R = \{(w_1, w_1), (w_2, w_2), \dots, (w_6, w_6)\} \circ \begin{bmatrix} (r_{11}, r_{11}) & (r_{12}, r_{12}) & (r_{13}, r_{13}) & (r_{14}, r_{14}) & (r_{15}, r_{15}) \\ (r_{21}, r_{21}) & (r_{22}, r_{22}) & (r_{23}, r_{23}) & (r_{24}, r_{24}) & (r_{25}, r_{25}) \\ (r_{31}, r_{31}) & (r_{32}, r_{32}) & (r_{33}, r_{33}) & (r_{34}, r_{34}) & (r_{35}, r_{35}) \\ (r_{41}, r_{41}) & (r_{42}, r_{42}) & (r_{43}, r_{43}) & (r_{44}, r_{44}) & (r_{45}, r_{45}) \\ (r_{51}, r_{51}) & (r_{52}, r_{52}) & (r_{53}, r_{53}) & (r_{54}, r_{54}) & (r_{55}, r_{55}) \\ (r_{61}, r_{61}) & (r_{62}, r_{62}) & (r_{63}, r_{63}) & (r_{64}, r_{64}) & (r_{65}, r_{65}) \end{bmatrix} \\ = \{(0.27, 0.27), (0.17, 0.17), (0.20, 0.20), (0.07, 0.07), (0.15, 0.15), (0.14, 0.14)\} \circ \begin{bmatrix} (0, 0) & (0, 0.2) & (0.35, 0.15) & (0.1, 0.2) & (0, 0) \\ (0, 0) & (0.1, 0.35) & (0, 0.2) & (0.25, 0.1) & (0, 0) \\ (0, 0) & (0, 0.25) & (0.4, 0.25) & (0.1, 0) & (0, 0) \\ (0, 0) & (0.2, 0.15) & (0.1, 0.2) & (0.25, 0.1) & (0, 0) \\ (0, 0) & (0.25, 0) & (0.35, 0.2) & (0, 0.2) & (0, 0) \\ (0, 0) & (0, 0.35) & (0.25, 0.1) & (0.1, 0.1) & (0.1, 0) \end{bmatrix} \\ = \{(0.07, 0.07), (0.14, 0.15), (0.1, 0.14), (0.14, 0.1), (0.07, 0.07)\} \tag{13}$$

After normalization,

$$B' = \left\{ \frac{(0.07, 0.07), (0.14, 0.15), (0.1, 0.14), (0.14, 0.1), (0.07, 0.07)}{0.07 + 0.07 + 0.14 + 0.15 + 0.1 + 0.14 + 0.14 + 0.1 + 0.07 + 0.07} \right\} \\ = \{(0.067, 0.067), (0.134, 0.143), (0.095, 0.134), (0.134, 0.095), (0.067, 0.067)\} \tag{14}$$

A histogram is drawn according to results, shown in Fig. 2. For every evaluation classification, there are three columns. The blue,

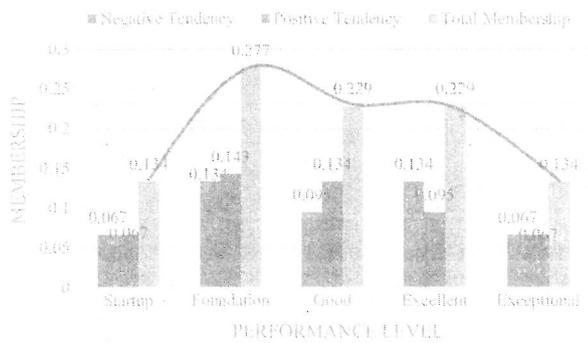


Fig. 2. Histogram of HSE performance dynamic fuzzy evaluation.

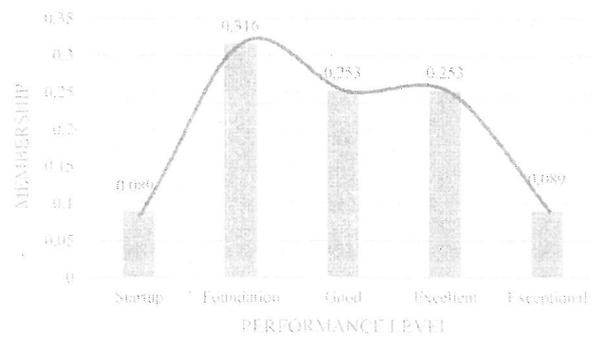


Fig. 3. Histogram of conventional HSE performance fuzzy evaluation.

red, and green columns respectively represent membership with negative tendency, membership with positive tendency, and the total membership for certain level.

As mentioned at the beginning of this paper, only the value is not enough to depict this gas transportation field's HSE performance. With regard to each level, tendency can be predicted by comparing membership with negative tendency and that with positive tendency. For startup and exceptional level, the overall membership is low and no tendency can be judged. So we can exclude the possibility of HSE performance being at startup or exceptional level. Although the membership at excellent level is a little high, the negative membership is larger than positive membership. So it is unreasonable to conclude HSE performance at this level. For foundation and good level, the total memberships are high and both of them are with positive tendency. We can roughly declare that the overall level of this gas transportation field's HSE performance is at foundation level according to maximum membership principle. Further, the positive tendency membership is higher than negative tendency membership, which means that the company's HSE performance is getting better from the perspective of dynamic analysis.

4. Comparison analysis

Traditionally, the HSE performance is determined only by membership without considering tendency. For comparison, the traditional static FCE method is applied to this case. Like the improved DFCE method, all the procedures of traditional FCE are similar except that all variables are static. For simplicity, only some key steps are shown here. The dynamic fuzzy relation matrix *R* is represented as:

$$R = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} \\ r_{21} & r_{22} & r_{23} & r_{24} & r_{25} \\ r_{31} & r_{32} & r_{33} & r_{34} & r_{35} \\ r_{41} & r_{42} & r_{43} & r_{44} & r_{45} \\ r_{51} & r_{52} & r_{53} & r_{54} & r_{55} \\ r_{61} & r_{62} & r_{63} & r_{64} & r_{65} \end{bmatrix} = \begin{bmatrix} 0 & 0.2 & 0.5 & 0.3 & 0 \\ 0 & 0.45 & 0.2 & 0.35 & 0 \\ 0 & 0.25 & 0.65 & 0.1 & 0 \\ 0 & 0.35 & 0.3 & 0.35 & 0 \\ 0 & 0.25 & 0.55 & 0.2 & 0 \\ 0 & 0.35 & 0.35 & 0.2 & 0.1 \end{bmatrix} \tag{15}$$

where every *r<sub>ij</sub>* is the membership degree of *u<sub>i</sub>* to evaluation level *v<sub>j</sub>*, regardless it is  $\bar{v}_j$  or  $\underline{v}_j$ . Similarly, the static factor weight set is described as *W* = {0.27, 0.17, 0.20, 0.07, 0.15, 0.14}. Then performance distribution set *B* is calculated and *B'* is obtained after normalization.

$$B = \{0.27, 0.17, 0.20, 0.07, 0.15, 0.14\} \circ \begin{bmatrix} 0 & 0.2 & 0.5 & 0.3 & 0 \\ 0 & 0.45 & 0.2 & 0.35 & 0 \\ 0 & 0.25 & 0.65 & 0.1 & 0 \\ 0 & 0.35 & 0.3 & 0.35 & 0 \\ 0 & 0.25 & 0.55 & 0.2 & 0 \\ 0 & 0.35 & 0.35 & 0.2 & 0.1 \end{bmatrix} = \{0.070, 0.25, 0.2, 0.2, 0.07\} \tag{16}$$

$$B' = \left\{ \frac{0.07, 0.25, 0.2, 0.2, 0.07}{0.07 + 0.25 + 0.2 + 0.2 + 0.07} \right\} = \{0.089, 0.316, 0.253, 0.253, 0.089\} \tag{17}$$

Fig. 3 provides the membership distribution of the total performance for every level. By comparing Figs. 3 and 2, it shows that dynamic fuzzy evaluation method provides not only consistent membership distributions as traditional FCE does, but also gives proactive results to help managers predict performance tendency.

5. Conclusions

Large-scale oil companies establish a set of criteria to evaluate HSE performance and many factors affecting HSE performance are included. However in the practical evaluation process, not every HSE performance indicator contributes significantly to HSE performance. Key HSE performance indicators used to be determined according to expert knowledge or experience. With the accumulation of data, historical materials could be a great treasure to assist evaluations. Spearman's rank correlation coefficient has been proven to be an effective method to identify key HSE performance factors base on statistical data. According to Spearman's correlation coefficient analysis of historical HSE evaluation data from a gas transportation field, six factors were identified as key performance indicators. They respectively are leadership and commitment, health, safety and environment mission, competence, training and awareness, control of documents, HSE management of contractor and suppliers, and incident/accident report, investigation and management. Managers can evaluate these key indicators more frequently to get an overview of the overall HSE performance. This can help to save time, human labor and financial resources. It should be noted that these identified key performance indicators may change with the increase of statistical data. This makes HSE performance evaluation more adaptable to changing circumstances.

As for the evaluation result, it has been expected to be comprehensive, objective and predictable. Fuzzy comprehensive evaluation

tion method has been used to obtain a comprehensive and objective result. In this paper, a dynamic fuzzy comprehensive evaluation method is proposed by improving conventional FCE method with dynamic fuzzy set theory. The evaluation result showed that a proactive HSE performance level can be obtained. It can provide managers a comprehensive picture of HSE performance, as well as the trend of HSE performance development.

Although the proposed methods were applied to a specific company in this paper, they can also be used in others cases. However, historical data is required to use Spearman's rank correlation coefficient to obtain key HSE performance indicators. Dynamic fuzzy comprehensive evaluation method presented the idea of taking potential trends of HSE

performance as one of evaluation criteria, which makes results more comprehensive.

**Acknowledgements**

The authors are grateful for the support provided by programs with China National Petroleum Corporation (CNPC) Research Institute of Safety & Environment Technology (Grant No. ANHY-F02-01-0002), National Science and Technology Major Project of China (Grant No. 2011ZX05055), and National Natural Science Foundation of China (Grant No. 51005247). The authors are also grateful for the valuable suggestion from employees and experts in China National Petroleum Corporation.

**Appendix A. Part of Zar's table (Zar, 1972)**

n	α								
	0.25	0.10	0.05	0.025	0.01	0.005	0.0025	0.001	0.005
4	0.600	1.000	1.000						
5	0.500	0.800	0.900	1.000	1.000				
6	0.371	0.657	0.829	0.886	0.943	1.000	1.000		
7	0.321	0.571	0.714	0.786	0.893	0.929	0.964	1.000	1.000
8	0.310	0.524	0.643	0.738	0.833	0.881	0.905	0.952	0.976
9	0.267	0.483	0.600	0.700	0.783	0.833	0.867	0.917	0.933
10	0.248	0.455	0.564	0.648	0.745	0.794	0.830	0.879	0.903
11	0.236	0.427	0.536	0.618	0.709	0.755	0.800	0.845	0.873
12	0.224	0.406	0.503	0.587	0.671	0.712	0.776	0.825	0.860
13	0.209	0.385	0.484	0.560	0.648	0.703	0.747	0.802	0.835
14	0.200	0.367	0.464	0.538	0.622	0.675	0.723	0.776	0.811
15	0.189	0.354	0.443	0.521	0.604	0.654	0.700	0.754	0.786

**Appendix B. HSE indicators' scores of a gas transportation station**

Data groups	Scores of 28 HSE indicators																												Sum
	n <sub>1</sub>	n <sub>2</sub>	n <sub>3</sub>	n <sub>4</sub>	n <sub>5</sub>	n <sub>6</sub>	n <sub>7</sub>	n <sub>8</sub>	n <sub>9</sub>	n <sub>10</sub>	n <sub>11</sub>	n <sub>12</sub>	n <sub>13</sub>	n <sub>14</sub>	n <sub>15</sub>	n <sub>16</sub>	n <sub>17</sub>	n <sub>18</sub>	n <sub>19</sub>	n <sub>20</sub>	n <sub>21</sub>	n <sub>22</sub>	n <sub>23</sub>	n <sub>24</sub>	n <sub>25</sub>	n <sub>26</sub>	n <sub>27</sub>	n <sub>28</sub>	
N <sub>1</sub>	75	54	85	25	59	19	49	14	38	55	37	32	25	70	54	21	23	44	170	36	56	63	17	36	35	23	65	60	1340
N <sub>2</sub>	82	46	66	24	46	22	52	18	41	67	36	25	20	76	51	17	22	50	174	31	52	69	20	34	33	36	63	53	1326
N <sub>3</sub>	98	66	80	28	55	25	67	10	35	53	45	34	22	80	57	29	30	38	180	34	61	72	15	44	20	31	78	50	1437
N <sub>4</sub>	90	64	72	18	51	16	46	13	46	50	51	31	23	73	60	26	31	32	144	20	58	74	18	52	29	29	72	57	1346
N <sub>5</sub>	67	72	74	30	57	18	78	19	44	68	35	24	31	74	48	23	34	45	155	22	51	83	14	41	48	34	52	73	1414
N <sub>6</sub>	71	74	81	27	62	20	64	12	37	61	42	29	28	69	56	18	29	35	157	28	65	77	21	63	34	27	49	61	1397
N <sub>7</sub>	88	68	69	22	48	26	47	21	58	74	48	30	32	82	61	28	32	49	179	35	57	67	25	68	53	18	79	49	1513
N <sub>8</sub>	96	62	63	20	58	28	58	15	49	65	41	27	34	67	49	25	27	52	181	30	53	68	19	48	57	37	71	72	1472
N <sub>9</sub>	101	78	98	26	65	21	55	17	39	78	49	38	27	75	63	19	28	57	169	29	60	84	29	57	56	40	48	85	1591
N <sub>10</sub>	99	76	90	32	67	23	61	16	45	72	40	35	33	79	66	20	33	46	178	32	59	81	27	46	59	38	69	84	1606

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Appendix C. Spearman's ranks and correlation coefficients  $R_s$ 

Ranks of total scores Y	Ranks of HSE affecting factor's scores																												
	X <sub>1</sub>	X <sub>2</sub>	X <sub>3</sub>	X <sub>4</sub>	X <sub>5</sub>	X <sub>6</sub>	X <sub>7</sub>	X <sub>8</sub>	X <sub>9</sub>	X <sub>10</sub>	X <sub>11</sub>	X <sub>12</sub>	X <sub>13</sub>	X <sub>14</sub>	X <sub>15</sub>	X <sub>16</sub>	X <sub>17</sub>	X <sub>18</sub>	X <sub>19</sub>	X <sub>20</sub>	X <sub>21</sub>	X <sub>22</sub>	X <sub>23</sub>	X <sub>24</sub>	X <sub>25</sub>	X <sub>26</sub>	X <sub>27</sub>	X <sub>28</sub>	
2	3	2	8	5	7	3	3	4	3	3	3	7	4	3	4	5	2	4	5	10	4	1	3	2	5	2	5	5	
1	4	1	2	4	1	6	4	8	5	6	2	2	1	7	3	1	1	8	6	6	2	4	6	1	3	7	4	3	
6	8	5	6	8	4	8	9	1	1	2	7	8	2	9	6	10	6	3	9	8	9	5	2	4	1	5	9	2	
3	6	4	4	1	3	1	1	3	8	1	10	6	3	4	7	8	7	1	1	1	6	6	4	7	2	4	8	4	
5	1	7	5	9	5	2	10	9	6	7	1	1	7	5	1	6	10	5	2	2	1	9	1	3	6	6	3	8	
4	2	8	7	7	8	4	8	2	2	4	6	4	6	2	5	2	5	2	3	3	10	7	7	9	4	3	2	6	
8	5	6	3	3	2	9	2	10	10	9	8	5	8	10	8	9	8	7	8	9	5	2	8	10	7	1	10	1	
7	7	3	1	2	6	10	6	5	9	5	5	3	10	1	2	7	3	9	10	5	3	3	5	6	9	8	7	7	
9	10	10	10	6	9	5	5	7	4	10	9	10	5	6	9	3	4	10	4	4	8	10	8	8	10	8	10	1	10
10	9	9	9	10	10	7	7	6	7	8	4	9	9	8	10	4	9	6	7	7	7	8	9	5	10	9	6	9	
$R_s$	0.67	0.73	0.33	0.33	0.5	0.53	0.24	0.24	0.31	0.64	0.32	0.50	0.67	0.37	0.60	0.22	0.49	0.44	0.39	0.12	0.33	0.38	0.55	0.52	0.72	0.44	0.13	0.43	

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