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Improving performance evaluation of health, safety and environment management system by combining fuzzy cognitive maps and relative degree analysis

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ABSTRACT

The performance evaluation of health, safety and environment management system (HSE-MS) is considered to be an effective way to eliminate out dated measures and help managers adopt proper rectification measures. The objective of this paper is to design a weight distribution model for HSE-MS performance evaluation, the importance of which stems from the current lack of integrated approaches for interpreting and ranking HSE-MS performance evaluation elements. Initially, Fuzzy Cognitive Maps (FCM) is adopted to illustrate the direct and indirect effects of HSE-MS elements on system performance indicators, and the results of FCM are used to develop leading factors helpful for decision making in an intensive management system. Then, the weight distribution from FCM is amended by Relative Degree Analysis (RDA), the aim of which is to combine the advantages of quantitative and qualitative knowledge-driven methods. Finally, the level of HSE-MS performance is obtained and analyzed. The whole performance evaluation framework highlights the potential correlations of evaluation elements as well as expert opinions, which will improve the reasonability of the HSE-MS performance evaluation.

1. Introduction

Health, Safety, Environment Management Systems (HSE-MS) is an integrated assistant tool composed of several factors such as organization framework, management task and operation specification. These factors form a structured management system through scientific fusion to eliminate injuries, adverse health effects and damages to the environment. From a functional perspective, its main objective is to conduct an advanced risk analysis to identify the hazardous consequences and consequently to hammer out appropriate loss control measures. Therefore, HSE-MS is considered to contribute to the profitability of the industry and it is broadly adopted by modern enterprises. HSE-MS in different fields is varied due to the unique characteristics of different industries. The specific requirements for constructing HSE-MS can refer to standards such as OHSAS18001 and ISO14000 (Abad et al., 2013; Gholami et al., 2015).

To ensure HSE-MS effective implementation, HSE-MS performance evaluation is carried out, which is conducted by an expert panel composed of relevance engineers, academic researchers, site operators and managers. Since HSE-MS performance evaluation can regulate, standardize and optimize HSE-MS in a proper manner, and timely eliminate out dated measures in management systems as well as continuously improve the performance of the enterprises, researches on HSE-MS performance evaluation are increasing during the last two decades. International Safety Rating System (ISRS) developed and first introduced in 1978 by Frank Bird is a widely used method to do HSE-MS performance evaluation, where experts are trained as auditors, and specially certified ISRS personnel will visit the sites and award one to five "stars" for safety performance at the site (Guastello, 1991). It can provide considerable benefits by addressing good or bad practices according to scores awarded by experts. However, a significant drawback of ISRS is lack of interrelationship reasoning metric among the evaluating factors, which could bring about inefficient and pointless workload. Considering that evaluating the performance of HSE-MS is not a simple exercise as a variety of variables are involved, many research work have been devoted to get a more scientific and reasonable evaluation result. The interrelationships of occupational health and safety, environment impacts and public satisfaction are well investigated (Azadeh et al., 2015) which proves that the elements of HSE-MS have specific correlative relation with each other. Shikdar

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et al. (2003) had also reported that a significant correlation exists among productivity indicators and health and organizational attributes. These inspires that certain elements of HSE-MS may significantly influence the overall performance and therefore must be considered and designed with more attention. A quantitative comparison analysis of strategy management models, with the purpose to screen better contractors according to their HSE-MS performance, is proposed based on accepted international standards within the framework of management Deming cycle (Abbaspour et al., 2012). This model provides quantitative evaluation measures of HSE-MS performance as a percentage of an ideal level with maximum possible score for each attribute. For improving the accuracy of information fusion, a model was developed to evaluate the maintenance performance using an analytical hierarchy process in ranking the weightings of the criteria set (Shen et al., 1998). Fuzzy Cognitive Maps (FCM) was first described by Bart Kosko in 1986. Recently an increasing number of publications are devoted to applications of FCM across a variety of fields, such as business planning, medicine, and environmental management. Relative Degree Analysis (RDA) aims to discover the correlation characters existing in big data to find out the rules of how the changes of some events cause the changes of the others. Quantitative model based on RDA constantly spring up. Lin et al. (2007) used grey relation analysis to explore the inter-relationships among different industrial sectors in Taiwan in order to provide an insight regarding sustainable development policy making. Asadzadeh et al. (2013) adopted FCM to analyze the integrated health, safety, environment (HSE) and ergonomics (HSEE). Through the integrated modeling for assessment of HSE-MS related elements with multi-path influences on workers' productivity, injury rate and satisfaction, it gives contributions to the solution of increasing problems associated with complex dynamical systems.

One of challenges of implementing HSE-MS performance evaluation is that, HSE-MS covers a broad range of programs ranging from human factors to work regulation, negotiation, organization and system design in macro-level, and in micro-level, each factor concerns with its underlying elements, in this sense, the HSE-MS elements have mass connecting metrics, and each element may have certain influence on the system performance as well as other elements. Thus the performance evaluation of HSE-MS should be a structured, and a well designed and integrated approach with respect to the insights of the complexity of HSE-MS elements is imperative Two key issues in system performance evaluation is that, one is the identification of evaluation score or description for each individual element, which displays the local performance of the system, and another one is to determine weight distribution, which represents the organization mechanism of local performances to reflect the holistic system performance. Since most HSE-MS performance evaluations depend on the scores given by expert opinions, and these scores are subjective, open and understood, exploring a deep view of weight distributions in evaluation system may give insight into illustrating the system performances. Therefore, it is required to investigate HSE-MS inner causal relationships to make the performance evaluation more oriented and pertinent.

This paper aims to: (i) develop a methodology reference framework for HSE-MS performance evaluation with the weight distribution of HSE-MS elements; and (ii) identify the causal ranks of HSE-MS elements to illustrate different influence levels on the sub-performance of job satisfaction, stuff productivity and society reputation as well as the over system performance. The proposed understanding of this allows enterprises with limited time and resources to prioritize their improvement measures and daily focuses. In addition, the research on weight distribution provides a more scientific and reasonable way to synthesize of experts' opinions.

2. The proposed methodology

The proposed methodology is based on the framework as shown in Fig. 1. Initially, the experts compare each item of the practical conditions in enterprises with the HSE-MS requirements mainly based on field investigations, face to face interviews and historical records. The better the evaluation item fits with the HSE-MS requirement, the higher score the evaluation item obtains (Step 1 and Step 2). Then, after each evaluation item score is obtained, the expert panel will assign a weight distribution representing how important the element is relative to the other element and to the whole system (Step 3). Following that ultimate evaluation score, the holistic HSE-MS performance can be calculated in many ways (Step 4). Finally, the outcome of the calculations could describe HSE-MS performance from expected perspectives. Various ranking methods are used to illustrate whether the HSE-MS is up to the standard (Step 5). It should be noted that the qualitative analysis is to afford foundations for quantitative calculation and limit the weight distribution to a reasonable level.

This paper mainly devotes to the research of Step 3 (marked red[1] color in Fig. 1) exploring the inner causal paths between HSE-MS elements, which could contribute to identify key elements that play vital roles on the consequences. Meanwhile, for the issue of weight distribution, comprising huge and interrelated detailed aspects of the HSE-MS elements, too objective or subjective deficiency of weight distribution of evaluation elements may result in an unbearable deviation to the whole system performance. Given that improving the weight distribution model is valuable.

Since it is a complex process to assign weights for evaluation elements based on experts' opinions, combing qualitative and quantitative approaches is a workable way to well integrate experiential knowledge, statistical data and computational technology. So FCM is employed to determine the weight distribution from the qualitative perspective owing to its excellent logical inference function, and RDA, owing to its simplicity and practicality, is adopted to supply necessary numerical correction for FCM from the quantitative perspective. This weight distribution model based on FCM–RDA includes 8 steps as following:

Step 1: A credibility weight is set for each of the P experts.
Step 2: Every expert is asked to make descriptions and comments on each of the N concept nodes.
Step 3: For each pair of concepts Ci and Cj, each expert is asked to use the If-Then rules to assign linguistic weights for the evaluating concepts. The If-Then rules are stated as following.
IF Ci change
THEN causes value of concept Cj change
THUS the influence of concept Ci on concept Cj is Weight (Ci, Cj)
Step 4: Select the comment sets of concept nodes to construct the FCM. The overall linguistic weight for each concept focuses on all direct and indirect paths.
Step 5: If quantitative data are available, RDA method is implemented into the data set to derive the correlation degree of concept nodes.
Step 6: Aggregate these linguistic weights and then some conflicting evaluating results for the concepts draw our special attention. Go back to the FCM mode and review causal paths among the arcs connecting conflicting concepts.
Step 7: Analyze the generated conflicting evaluating results based on historical records, managers' communications or field inspections. The credibility weight of experts is adjusted by the corresponding credibility weight.

[1] For interpretation of color in Figs. 1 and 6, the reader is referred to the web version of this article.

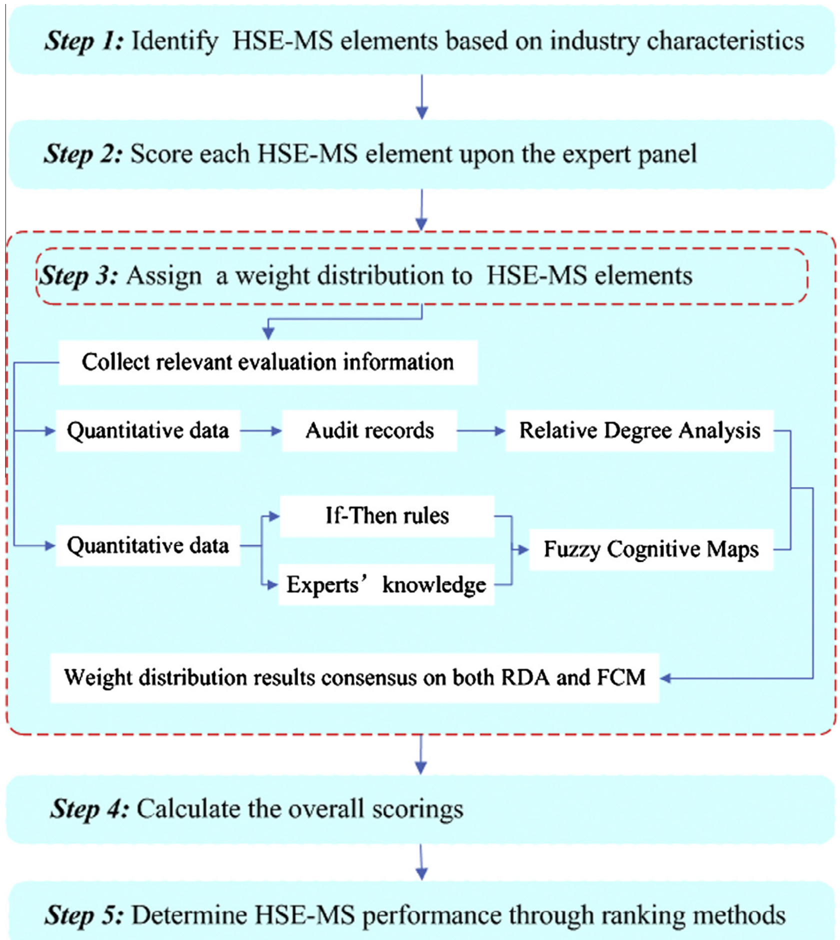

Fig. 1. The schematic of implementing HSE-MS performance evaluation.

Step 8: Go through the FCM–RDA framework again.
IF there is no conflicting concept, go to the step of decision prediction
ELSE reconstruct the weight matrix of FCM.
END.

3. Theoretical foundation of the developed weight distribution model

3.1. Fuzzy Cognitive Maps (FCM)

FCM is a causal knowledge-driven methodology for modeling complex decision systems, originated from the combination of fuzzy logic and neural networks. This fuzzy technique incorporates the accumulated experience and knowledge by employing experts who are aware of system operations and behavior in different situations, and then gives the hidden pattern of the issue.

Experts determine concepts, interconnections, and assign casual fuzzy weights to the interconnections. However, the strength of the data depends on the available number of expert opinions. FCM as a graphically framework includes concept nodes and weighted arcs. It signs each weight graph with feedback to illustrate the connection strength. In general, concepts of a FCM represent leading factors as well as characteristics of the modeled integrated system and stand for basic events, required goals, system performance, running states and trends of the target units. Signed weighed arcs and connected concept nodes represent the interrelated relationships that exist among different concepts. This graphic display shows clearly which concepts can exert influences on other concepts and how much the influence is (Kim and Lee, 1998).

FCM nodes are named by such concepts forming the set of concepts C = {C1, C2, . . ., Cn}. Arcs (Cj, Ci) represent the interrelated links between different concepts. Weights of arcs are associated with a weight value matrix Wn·n, where each element of the matrix w_{ji} takes values in an interval of $(-1,1)$. Fig. 2 is a simple example of cyclic FCM model. Suppose that we are interested in calculating the total effects of C1 on C5. According to the fuzzy causal algebra (Pelaez and Bowles, 1996), assume the causal values are given by a set of P = {none, weak, medium, strong, very strong}. There are three causal paths from C1 to C5: path (C1, C3, C5), path (C1, C2, C4, C5) and path (C1, C3, C4, C5). The three indirect effects of C1 to C5 are:

Path 1: P (C1–C3–C5) → I_1(C1, C3, C5) = min {e_{13}, e_{35}) = min {strong, very strong} = weak
Path 2: P(C1–C2–C4–C5) → I_2(C1, C2, C4, C5) = min{e_{12},e_{24},e_{45}} = min{weak, very strong, medium} = weak
Path 3: P(C1–C3–C4–C5) → I_2(C1, C3, C4, C5) = min{e_{13},e_{34},e_{45}} = min{strong, weak, medium} = weak

Hence, the total effect of C1 on C5 is: T (C1, C5) = max {I_1, I_2, I_3} = max {weak, weak, weak} = weak. In words, C1 can be said to impart weak interrelationship to C5.

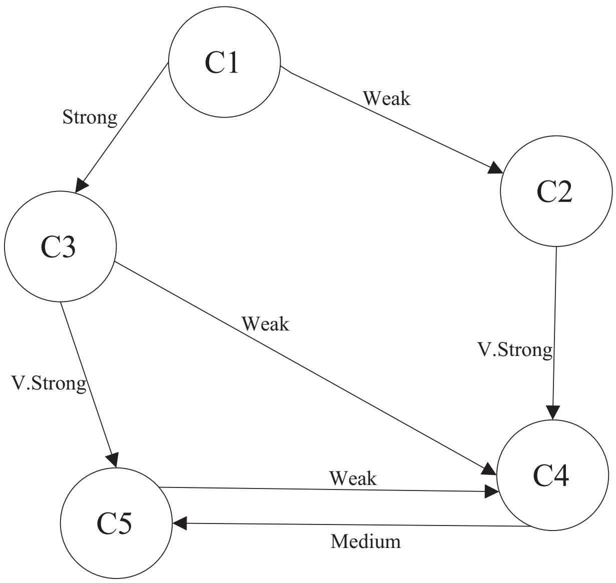

Fig. 2. Example of a cyclic FCM with labels at the edges.

Indirect effect is an effect that one concept has influence on another concept via an intermediate concept in FCM. Generally, there are large or infinite numbers of indirect effects on this FCM. Similarly eight-edge paths, nine-edge paths, and the list goes on. This procedure can be calculated through computer assistant and all of the indirect effects can be drawn.

By mapping fuzzy expressions to numerical value in an interval of $(-1,1)$, all the comments by expert linguistic variables are considered and an overall linguistic weight is obtained. However, in many complicated systems, the calculating results from FCM may become conflicted with scoring methods or other expert opinions. This is due to the intervention by utilizing subjective reasoning rules. So it is necessary to propose a framework for extracting fuzzy interconnections among attributes from available data. In the following Section 3.2, a statistic method will be introduced as knowledge extraction to improve the assessment results of FCM.

3.2. Relative Degree Analysis (RDA)

RDA is an information-processing paradigm to explore quantitative relationships between evaluating elements. It is made up of simple processing units, which are linked by numerical connections to form structures that are able to learn relationships between sets of variables. RDA results can be used to describe the magnitude of interrelation impacts. The procedure for implementing this method contains the main three steps as following:

Step 1: Identification of analytical sequences

In line with the qualitative analysis of researching object, we can identify a dependent variable factor and multiple independent variable factors. Suppose that X_0 is a reference sequence consisting of dependent variable data. Usually, X_0 is selected according to practical requirements. Then, the multiple independent variable factors will build a comparing sequence $X_i(i = 1,2,\ldots,n)$. Generally, the original series possess different orders of magnitude. To achieve the reliability of analysis results, sequences of variable parameters need to be nondimensionalized. After that, Eq. (1) is constructed by $n + 1$ pieces of data.

$$(X_0, X_1, \ldots X_n) = \begin{bmatrix} x_0(1) & x_1(1) & \cdots & x_n(1) \\ x_0(2) & x_1(2) & \cdots & x_n(2) \\ \cdots & \cdots & & \cdots \\ x_0(N) & x_1(N) & \cdots & x_n(N) \end{bmatrix}_{N\times(n+1)} \quad (1)$$

where N represents the length of the variable sequence. X_0 is general selected as a proper unit possessing the best quality.

Step 2: Determination of the difference among analytical sequences

Calculate the difference between the first column and the others. Eq. (2) shows the absolute differences.

$$\Delta'_{0i}(k) = \begin{bmatrix} \Delta_{01}(1) & \Delta_{02}(1) & \cdots & \Delta_{0n}(1) \\ \Delta_{01}(2) & \Delta_{02}(2) & \cdots & \Delta_{0n}(2) \\ \cdots & \cdots & & \cdots \\ \Delta_{01}(N) & \Delta_{02}(N) & \cdots & \Delta_{0n}(N) \end{bmatrix}_{N\times n} \quad (2)$$

$\Delta_{0i}(k) = |x_0(k) - x_i(k)|\ i = 1,2,\ldots,N;\ k = 1,2,\ldots,n.$

Step 3: Calculation of relevant coefficients and relevant degrees

The relevant coefficient is constructed as Eq. (3).

$$\xi_{0i}(k) = \frac{(Min_iMin_k|\Delta_{0i}(k)| + \rho Max_iMax_k|\Delta_{0i}(k)|)}{(|\Delta_{0i}(k)| + \rho Max_iMax_k|\Delta_{0i}(k)|} \quad (3)$$

where resolving ratio ρ is within the interval of $(0,1)$. The bigger ρ is, the greater its resolving power is. As for Eq. (3), the value of ρ reflects the degree to which the minimum scores are emphasized relative to the maximum scores. The maximum and minimum difference is respectively the largest and smallest number of each row.

After calculating $\xi_{0_i}(k)$, the relevant coefficient of the ith sequence to the referenced sequence can be calculated according to Eq. (4):

$$r_{0i} = \frac{1}{N}\sum_{k=1}^{N}\xi_{0i}(k) \quad (4)$$

where the bigger value of r_{0i}, the closer relationship between the ith sequence and the referenced sequence (Tonidandel and LeBreton, 2011).

4. Implementation: HSE-MS performance evaluation

4.1. Identify the evaluation elements for HSE-MS performance

The selected case study for this research is an oil and gas transportation plant located in China. This plant is engaged in developing and implementing proper HSE-MS. For evaluating the HSE-MS performance execution status, a considered correspondence sheet has been developed to audit whether the HSE-MS of the plant is conformable to the present standards. The standards of OHSAS 18001:2007, ISO 14001:2004 and ILO-OSH 2001 are the main references that were taken into account by the evaluation expert panel.

The HSE-MS performance is evaluated from three aspects (job satisfaction, staff productivity and society reputation). The HSE-MS is given shape to three categories (human, facility and environment), and each of the category contains their own elements. Fig. 3 shows the content of elements for the HSE-MS performance evaluation based on the Delphi technique.

4.2. Analyze the interrelation of HSE-MS elements and sub-performances using FCM

The number of HSE-MS elements is selected as 13 (H1, H2, H3, H4, H5, F1, F2, F3, F4, F5, E1, E2 and E3 as listed in Fig. 3). However, there are far more than 13 HSE-MS elements in practice. The reduction of the number is to avoid the complexity of the proposed

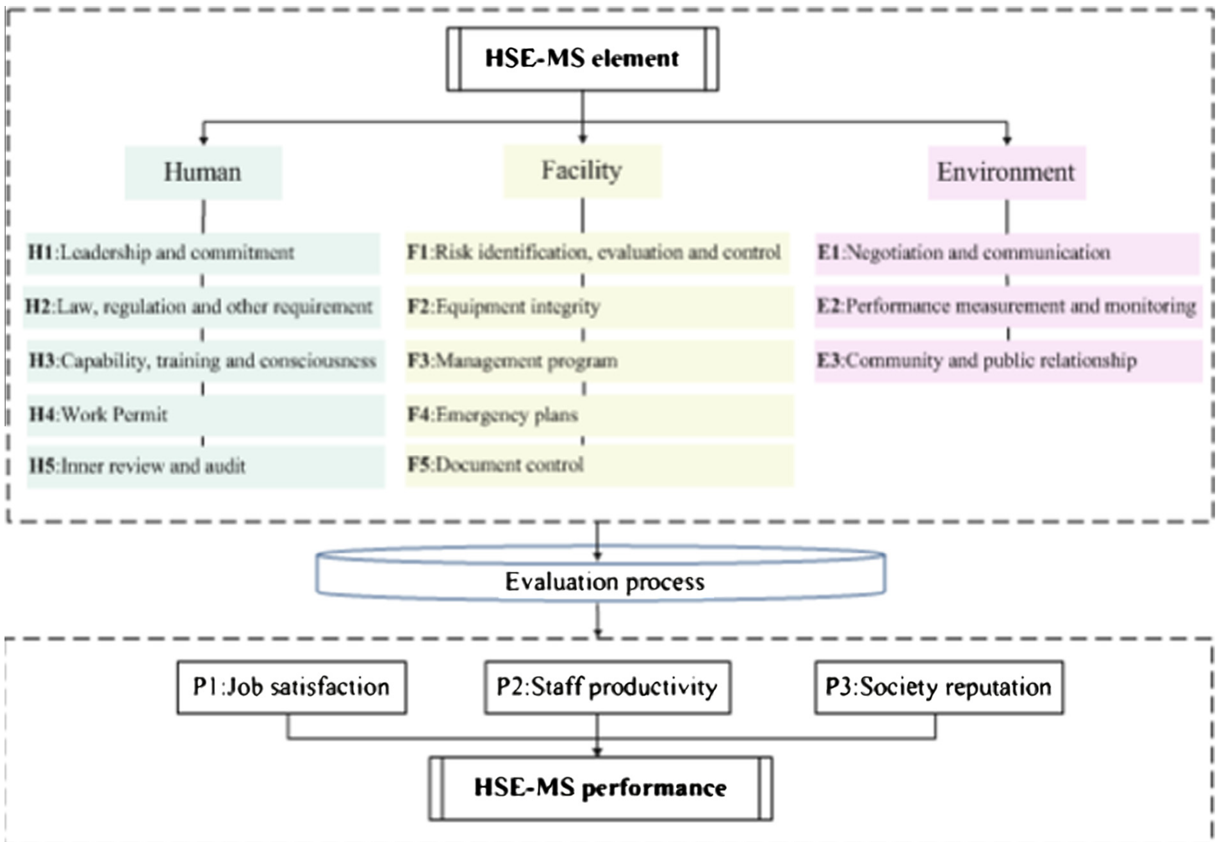

Fig. 3. The structure of evaluation elements for HSE-MS performance.

FCM model and to be more clear to no specialist readers. These 13 elements and 3 sub-performances (P1, P2 and P3) work as the concept nodes of the FCM model. Table 1 gathers these respective elements, the sub-performance and the weights among each pair of FCM concept nodes. The suggested weight to each pair of concepts is assigned as one of {zero, weak, medium, strong, very strong}. The promotion of each concept nodes is to improve the system performance, and the influence tendency between each pair of the concept nodes is positive. Table 1 can be also viewed as a connection matrix. For example, in column 2 and row 2, V.S means that H1 plays very strong role on H2. In column 9 and row 3, S means that H2 plays strong role on F3.

Through the FCM algorithm described in Section 3.1, the values of weight vector representing the impact of each concept on each sub-performance are obtained:

W_{p1}=[S,S,M,S,S,S,M,M,W,W,S,M,W]
W_{p2}=[S,M,S,S,S,M,M,M,0,W,S,S,W]
W_{p3}=[S,V.S,M,S,S,S,W,M,W,W,V.S,S,S]

It is accepted that in a hierarchical evaluation process different sub-performance have different impact degrees on the final performance. In this paper, we assume the three sub-performances job satisfaction, staff productivity and society reputation have the same evaluating weight.

Based on the number of causality paths extracted in FCM, a diagram of causality ranks is developed (Fig. 4), which clusters HSE-MS elements. The more this concept of influence, the lower the rank of causality to which concept *i* belongs.

In the clustering of Fig. 4, the concept with a number of first-level indirect path between 13 and 11 belongs to the rank 1. Rank 2 contains factors with number of the first-level indirect paths between 10 and 8. Rank 3 between 7 and 5 and rank 4 between 4 and 2. Within each rank, the concepts are organized so that concepts with closer distance to the final output have greater influences compared to other concepts.

The results of causal ranking in Fig. 4 illustrate that excellent leadership and commitment (H1) can be considered among the root causes of remarkable job satisfaction, staff productivity and society reputation. Basic evaluating factors, such as work permit (H4), emergency plans (F4), document control (F5) and community and public relationship (E3) are the most influenced by other evaluating factors. Staff productivity belongs to the last level of causality indicating that it is mostly complicated and influenced by the other factors, which is according with the real estimations.

4.3. Calculate the correlation degree of HSE-MS elements based on RDA

To ensure the safety and effective running of the HSE-MS, a complete inspection auditing is carried out for the oil and gas transportation plant every two years. Therefore, we select the audit records over the period 2002–2012, which will give a numerical reference to adjust the obtained weight distribution using FCM. The initial auditing results are shown in Table 2. The experts compare each element with the reference standards, and then give each element a score to represent its consistency with the required standards. The higher the consistency degree is, the higher score the element receives (full mark for each element is 100).

Through the algorithm (Section 3.2), RDA sequences derived from HSE-MS auditing records are listed in Table 3, where the average score of the 13 elements of each period is selected out as the referenced sequence X_0.

Table 4 shows the differences between the evaluating sequences and the referenced sequences.

Table 1
The global FCM connection matrix based on expert knowledge.

Node	H1	H2	H3	H4	H5	F1	F2	F3	F4	F5	E1	E2	E3	P1	P2	P3
H1	0	V.S	0	0	0	W	0	M	M	W	S	M	S	M	S	M
H2	0	0	0	0	V.S	V.S	0	S	S	0	V.S	V.S	0	W	W	0
H3	S	0	0	0	0	V.S	0	W	0	M	W	0	0	W	S	M
H4	0	0	V.S	0	S	S	0	0	0	0	0	M	S	0	0	0
H5	M	0	S	0	0	S	0	M	0	M	M	0	0	S	0	V.S
F1	M	0	0	0	S	0	W	S	V.S	M	0	M	0	0	0	M
F2	0	0	0	0	0	W	0	M	W	0	W	W	0	0	0	0
F3	0	0	M	0	W	W	0	0	S	0	W	W	0	M	M	0
F4	0	0	0	0	W	W	0	0	0	0	0	0	0	0	0	W
F5	W	0	0	0	W	0	W	W	0	0	0	S	0	W	0	0
E1	M	0	M	0	0	0	0	W	0	0	0	S	V.S	S	M	V.S
E2	S	0	W	0	0	0	0	M	S	M	W	0	M	M	0	S
E3	W	0	0	0	0	0	0	W	0	0	S	W	0	W	0	S
P1	M	0	0	0	0	0	0	0	0	0	W	0	W	0	S	M
P2	M	0	0	0	0	0	0	0	0	0	0	0	0	M	0	W
P3	S	0	0	0	0	0	0	0	0	0	M	0	M	W	0	0

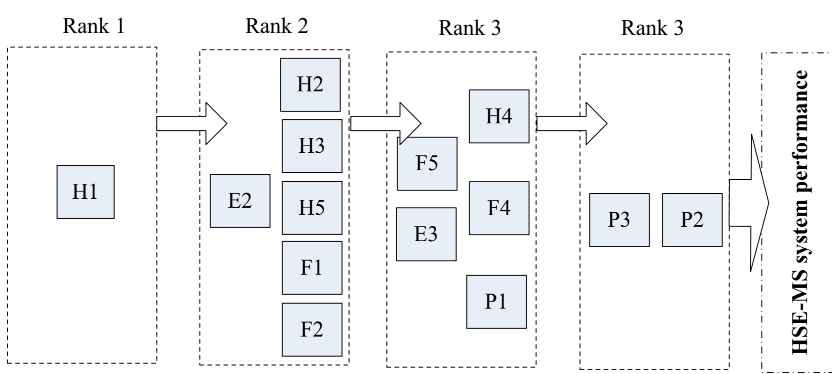

Fig. 4. The causal ranks of HSE-MS elements and system sub-performance.

Table 2
Original data from experts based on HSE-MS auditing records from 2002 to 2012.

Time/concept	H1	H2	H3	H4	H5	F1	F2	F3	F4	F5	E1	E2	E3
2002–2004	64	70	60	68	64	68	69	65	69	75	68	69	77
2004–2006	73	68	67	66	75	64	68	68	80	73	70	73	70
2006–2008	67	73	71	70	79	66	70	78	78	75	76	78	75
2008–2010	68	75	71	73	71	69	75	77	70	72	81	70	72
2010–2012	73	73	74	62	77	74	62	73	80	80	85	73	92

Here ρ is adopted as 0.5. Table 5 shows the correlation coefficients of each sequence to the referenced sequence, and then Table 6 shows the result of r_{0i} after normalization.

To interpret these numerical influences as linguistic variables to match the FCM assessing results, the semantic rule *M* is defined as follows and these terms are characterized by fuzzy sets whose membership functions are shown in Fig. 5 (Lin and Lee, 1996). The linguistic variables that describe each interconnection are combined and the overall linguist variable will be transformed in the interval (0, 1). A numerical weight for each interconnection will be the outcome of the defuzzifier.

M (zero) = the fuzzy set for "an influence close to 0" with membership function μ_z
M (weak) = the fuzzy set for "an influence close to 0.25" with membership function μ_w
M (medium) = the fuzzy set for "an influence close to 0.50" with membership function μ_m
M (strong) = the fuzzy set for "an influence close to 0.75" with membership function μ_s
M (very strong) = the fuzzy set for "an influence above to 0.75" with membership function $\mu_{v.s}$

The relevant coefficient yielding from RDA is illustrated by quantitative description based on *M* rule. The values of weight vector representing the impact of each concept on the whole system sub-performance are obtained:

W_p = [V.S,W,S,M,S,S,M,M,V.S,M,M,M,S]

4.4. Determine the weight distribution based on FCM and RDA

The comparing results of FCD and RDA are shown in Fig. 6. The linguistic descriptions of each evaluating element impacting on the system performance are illustrated as clustering columns with respect to clearly represent the conflicted evaluating results.

As seen in Fig. 6, three HSE-MS factors marked with red ellipse H2 (Law, regulation and other requirement), F4 (Emergency plans) and E1(Negotiation and communication) have significant difference gap in relative degrees driven form FCM and RDA method

Table 3
RDA sequences derived from HSE-MS auditing records.

No./Sequence	X_0	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}
1	68	64	70	60	68	64	68	69	65	69	75	68	69	77
2	70	73	68	67	66	75	64	68	68	80	73	70	73	70
3	73	68	75	71	73	71	69	75	77	70	72	81	70	72
4	74	67	73	71	70	79	66	70	78	78	75	76	78	75
5	75	73	73	74	62	77	74	62	73	80	80	85	73	92

Table 4
Differences between the evaluating sequences and the referenced sequences.

Time/Δ_{0i} (k)	Δ_{01}	Δ_{02}	Δ_{03}	Δ_{04}	Δ_{05}	Δ_{06}	Δ_{07}	Δ_{08}	Δ_{09}	Δ_{010}	Δ_{011}	Δ_{12}	Δ_{013}
1	4	2	8	0	4	0	1	3	1	7	0	1	9
2	3	2	3	4	5	6	2	2	10	3	0	3	0
3	5	2	2	0	2	4	2	4	3	1	8	3	1
4	7	1	3	4	5	8	4	4	4	1	2	4	1
5	2	2	1	13	2	1	13	2	5	5	10	2	17

Table 5
Correlation coefficients of each sequence to the referenced sequence.

No./$\Delta_{0_i}(k)$	$\xi_{01}(n)$	$\xi_{02}(n)$	$\xi_{03}(n)$	$\xi_{04}(n)$	$\xi_{05}(n)$	$\xi_{06}(n)$	$\xi_{07}(n)$	$\xi_{08}(n)$	$\xi_{09}(n)$	$\xi_{10}(n)$	$\xi_{11}(n)$	$\xi_{12}(n)$	$\xi_{13}(n)$
1	1.89	1.44	2.78	1.00	1.89	1.00	1.22	1.67	1.22	2.56	1.00	1.22	3.00
2	1.6	1.4	1.6	1.8	2	2.2	1.4	1.4	3	1.6	1	1.6	1
3	2.25	1.5	1.5	1	1.5	2	1.5	2	1.75	1.25	3	1.75	1.25
4	2.75	1.25	1.75	2	2.25	3	2	2	2	1.25	1.5	2	1.25
5	1.11	1.11	1.00	2.26	1.11	1.00	2.26	1.11	1.42	1.42	1.95	1.11	2.68

Table 6
Relevant coefficient of the *i*th sequence to the referenced sequence after normalization.

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}
r_{0i}	1.00	0.00	0.67	0.47	0.71	0.86	0.59	0.50	0.93	0.48	0.60	0.34	0.86

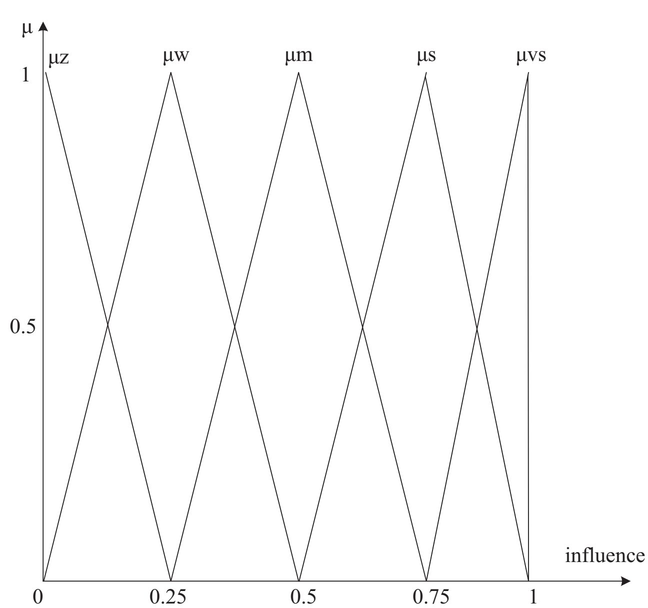

Fig. 5. Terms of the linguistic variable influence.

(As the level of their difference gaps across two levels, this situation requires more attention). How is this significant difference gap to be explained? Take F4 for example, the arcs of (F4, P1), (F4, P2), (F4, P3), (F5, P1), (F5, P2), (F5, P3), (E3, P1) and (F3, P2) are extracted to discuss the crucial distinction between the qualitative and quantitative knowledge-based weight distribution results.

In FCM model, take (F4, P1) for example, the arcs of which are listed to illustrate individual causal paths:

Path 1 from F4 to P1: (F4,H5) → (H5,P1) = {W,S}
Path 2 from F4 to P1: (F4,H5) → (H5,H1) → (H1,P1) = {W,M,M}
Path 3 from F4 to P1: (F4,H5) → (H5,H3) → (H3,P1) = {W,S,W}
Path 4 from F4 to P1: (F4,H5) → (H5,F3) → (F3,P1) = {W,M,M}
Path 5 from F4 to P1: (F4,H5) → (H5,F5) → (F5,P1) = {W,M,W}
Path 6 from F4 to P1: (F4,H5) → (H5,E1) → (E1,P1) = {W,M,S}
Path 7 from F4 to P1: (F4,H5) → (H5,P3) → (P3,P1) = {W,V.S,W}
Path 8 from F4 to P1: (F4,F1) → (F1,H1) → (H1,P1) = {W,M,M}
Path 9 from F4 to P1: (F4,F1) → (F1,H5) → (H5,P1) = {W,S,S}
Path 10 from F4 to P1: (F4,F1) → (F1,F3) → (F3,P1) = {W,S,M}
Path 11 from F4 to P1: (F4,F1) → (F1,F5) → (F5,P1) = {W,M,W}
Path 12 from F4 to P1: (F4,F1) → (F1,E2) → (E2,P1) = {W,M,M}
Path 13 from F4 to P1: (F4,F1) → (F1,P3) → (P3,P1) = {W,M,W}

As seen above, a small number (less than 21%) of linguistic comment "weak" is shown in the intermediate paths. The weight values in intermediate paths suggest the influence of F4 does to P1 via other concepts. So the key segments leading weak interrelationship between F4 and P1 is the comments on (F4, H5) and (F4, F1). It is noted that experts were asked to express their opinions about the paired concepts of F4 and other HSE-MS evaluating elements, the linguistic weigh only reflects the impacting amount of the two paired concepts from a local viewpoint. However, the reasoning rules based on fuzzy causal algebra performs poorly under complicated systematic evaluation since the Min–Max approach could decrease the assessment accuracy.

To eliminate the conflicting evaluation results, detailed scenario analyses are carried out to calculate how F4 can impact the system performance and which aspects of F4 need to be reviewed. Since

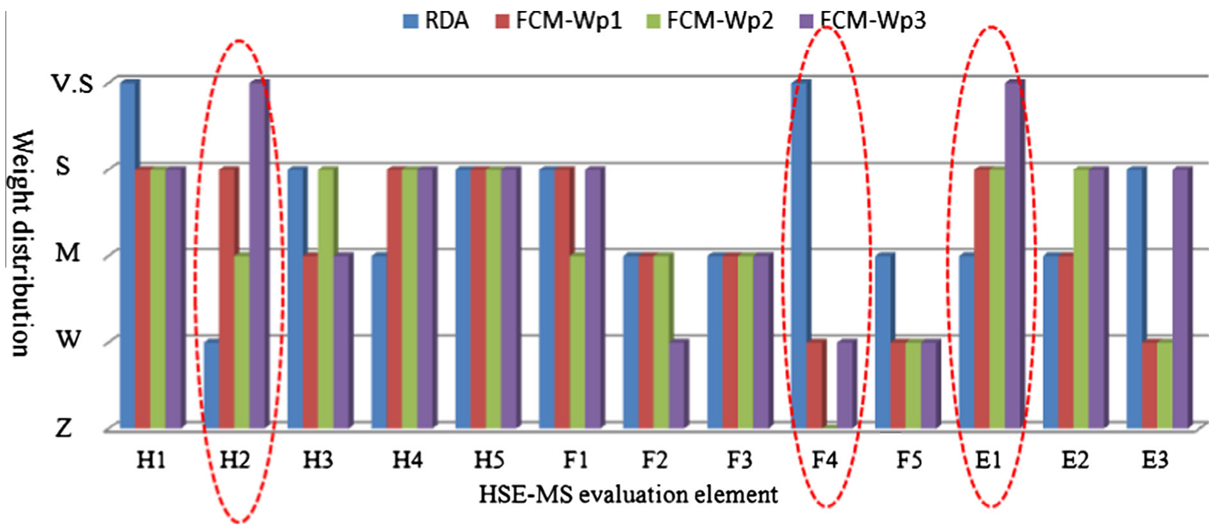

Fig. 6. The comparison effects of HSE-MS factors on system performance indicators based on FCM and RDA.

Table 7
Questionnaire for revising influences for emergency plans on the HSE-MS elements and sub-performance.

Item	H1	H2	H3	H4	H5	F1	F2	F3	F4	F5	E1	E2	E3	P1	P2	P3
Coordination	√			√	√		√	√	√		√	√	√	√		
Liaison			√	√	√			√		√	√		√		√	√
Co-operation			√		√			√	√		√	√	√	√	√	√
Training		√	√		√	√	√	√	√			√		√	√	√
Updating	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Practices			√		√	√		√				√				
Coordination	√			√	√		√	√	√		√	√	√	√		

Table 8
HSE-MS performance evaluation for 2002–2012.

Time/sub-performance	P1	P2	P3
2002–2004	67.4	67.03	68.06
2004–2006	70.1	70.03	70.18
2006–2008	72.7	72.69	72.82
2008–2010	73.1	73.28	73.53
2010–2012	74.27	74.07	75.91

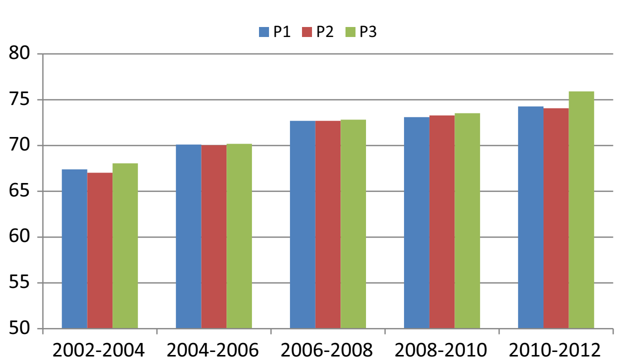

Fig. 7. The HSE-MS performances during 2002–2014.

emergency plans enable a quick and effective response to unplanned incidents, it should be well prepared and workers should be trained to act as per these orders in the event of an emergency. The content of emergency plans includes coordination, liaison and co-operation between different agencies, enforcing scheduled training, refresher courses and demonstration and mock practices to those concerned-rescue and recovery crews, trained staff and others. In order to address emergency plan related factors that may affect system performance, Table 7 is designed for adjustments for specific causal impacts (Mousavi et al., 2011). If the expert panel believes an element has close interrelationship with an item of the emergency plans, then a tick will be given to the corresponding position.

By adding the ticked points shown in Table 7, the concept of emergency plans is believed to make a significant contribution to the system performance. Considering the above analysis, the initial weight value of (F4, P1) is suggested to raise one level. Following the same way, it is possible to eliminate all the conflicting concepts. Through synthesizing the results of FCM–RDA, the final weight distributions of the 13 elements for the three sub-performances are:

$$W_{p1} = [S,S,M,S,S,S,M,M,M,W,S,M,W]$$
$$W_{p2} = [S,M,S,S,S,M,M,M,W,W,S,S,W]$$
$$W_{p3} = [S,V.S,M,S,S,S,W,M,M,W,V.S,S,S]$$

4.5. HSE-MS performance evaluation results

The overall result of the HSE-MS performance evaluation can be obtained by putting the specific score of Table 2 into the final weight distribution. Then the HSE-MS performance evaluation of 2002–2012 year is listed as Table 8. Since the final weight distributions are qualitative, to invert them into quantitative description, *M* rule is again obtained, V.S = 1.0, S = 0.75, M = 0.5 and W = 0.25.

Fig. 7 shows the HSE-MS performance trends over 2002–2012. It can be seen that the level of HSE-MS performance has improved steadily. Through analyzing the three aspects of system performance (P1, P2 and P3), no significant difference has been figured out, which is to say the effort degree of each of

HSE-MS measure is balanced, and the result is correspondence to actual conditions.

5. Conclusion

The essence of carrying out a HSE-MS performance evaluation includes multiple processes, which suggests that we can make a combination effort to improve the reasonability by considering such as the determination of HSE-MS elements and weight distribution models. Since the elements of HSE-MS covers different aspects, the HSE-MS performance should not be tracked into one single direction. Additionally, the shortcoming of over subjective or over objective weight distribution is obvious. To address these issues, an improved HSE-MS performance evaluation is proposed and applied to a case study (1) to structure the HSE-MS evaluation elements and (2) design a weight distribution model combining the knowledge of qualitative fuzzy cognitive maps and quantitative relative degree calculations.

The contributions of the proposed work is that (1) important health, safety, environment elements as well as system sub-performances are determined and structured and then through the use of FCM, according to which we mapped the knowledge of experts about the relationships between these elements and showed their cause and effect relations and then constructed leading indicators for system performance, and (2) in the proposed weight distribution model developed based partly on FCM partly on RDA, all the available knowledge from data was used to enrich the FCM which works as a knowledge-based decision making model, thus can better handle the expert opinions.

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