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Safety Culture Construction Evaluation Based on Combination Weighting and Fuzzy TOPSIS Methods

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Safety culture plays an important role in the prevention of accident. Positive safety culture can effectively improve worker's safety conscious and reduce the accident rate. This paper is aimed to present a fuzzy decision making method for objectively evaluating enterprise safety culture construction level. Based on evaluation indicators of safety culture construction level, combination weighting method in view of spearman rank correlation coefficient was adopted to determine weights of evaluation indicators, andfuzzy technique for order preference by similarity to an ideal solution (fuzzy TOPSIS) of safety culture construction level was proposed by introducing triangular fuzzy number. Filing in four Chinese companies as an example to carry on comprehensive evaluation, evaluation results show that the proposed method can reflect actual situation of enterprise safety culture construction level.

1. Introduction

Safety culture has a positive effect on employees' safety conscious and behaviour, as well as enterprises' safety in production, which has aroused much attention of authorities and enterprises. However, due to the lack of an effective evaluation system, a lot of enterprises are unable to judge the level of safety culture and construct safety culture. Therefore, how to evaluate the construction level of safety culture has become one of the most important issues.

Great progresses have been made both at home and abroad in the profound research on evaluation of safety culture construction level. For example, (Cox and Cheyne, 2000) established an organizational safety culture assessment system by using factor analysis method. Based on Hudson's safety culture model, (Filho et al., 2000) constructed the safety culture evaluation system through multifactor interrelation analysis. (Mariscal et al., 2012) made use of the RADAR logic (Results, Approach, Deployment, Assessment and Review) of the EFQM model as a tool for the self assessment of safety culture in a nuclear power plant. (Qian and Li, 2009) applied rough set and neural network to the research of aviation safety culture assessment and constructed the assessment model. To sum up, these studies seldom take account into one characteristic of safety culture evaluation factors- the uncertainty or fuzziness, it may cause a great difference between evaluation result and the actual situation. However, based on the fuzzy theory, the fuzzy TOPSIS method which considers fuzziness of the factors could evaluate the complicated problems more objectively and obtain more accurate results.

According to the fuzziness of safety culture evaluation indicators, we confirm the weight by using combination weighting approach which based on the spearman rank correlation coefficients, and propose the fuzzy TOPSIS evaluation method by introducing triangular fuzzy number. It is expected to provide references for the evaluation of enterprises' safety culture level.

2. Evaluation indicators of enterprise safety culture construction level

Behavior-based "2-4" model for accident causation has been proposed by research team in the process of exploring what the cause of the accident is. Behavior-based "2-4" model is presented in table 1. It can be seen from table 1, the accident causation chain consists of two separated levels, namely, organizational and individual behavior, and two stages as guiding behavior and operating behavior at organizational level, and two stages as habitual behavior and act at individual level, which respectively covers from root, radical,

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indirect to direct reasons of an accident. More specifically, they include the organizational safety culture, safety management system, personal safety knowledge, safety consciousness, safety habits, personal unsafe act and unsafe conditions (Fu et al., 2013).
Based on a narrow definition of safety culture that safety culture is safety concept, combined with behavior-based “2-4” model for modern accident causation, the evaluation indicator system of enterprise safety culture construction level which includes 9 evaluation indicators was proposed from two aspects of safety culture and its results. The evaluation indicators are also presented in Table 1.

Table 1: Behavior-based “2-4” model and evaluation indicators of safety culture construction level

Name of the chain	Behavior developing process Organizational behavior		Individual behavior		Consequence	
Developing stage	Guiding behavior	Operating behavior	Habitual behavior	Act	Accidents	Loss
Types of causes	Root cause	Radical cause	Indirect cause	Direct cause	Accidents	Loss
Causation chain of accidents	Safety culture	Safety management system	Safety knowledge Safety consciousness Safety habits	Unsafe acts Unsafe conditions	Accidents	Loss
Evaluation indicators	Status of safety thoughtsU_1 Comprehensibility of safety thoughtsU_2 Status of safety culture carriersU_3	Quality of safety management systemU_4	Quality of safety training U_5	Status of employees violationU_6 Investigation situation of physical hidden danger U_7	Quality of accident statistics U_8 Safety performance U_9	

3. Combination weighting methods based on Spearman rank correlation coefficient

Methods to determine the weight of evaluation indicator are divided into subjective and objective weighting methods. Subjective weighting method can reflect the intention of decision makers, and has a certain degree of subjectivity. Objective weighting method has a mathematical basis, but ignores the subjective information of decision makers, without considering the difference of the indicator itself. Subjective and objective combination weighting methods based on Spearman rank correlation coefficient, combines the advantages both subjective and objective weighting methods, makes the indicator weight to reflect the actual situation. Therefore, this method can be used to determine the weight of evaluation indicator of safety culture construction level. The specific steps are as follows.
1) Using P kinds of subjective weighting methods and Q kinds of objective weighting methods, respectively, to calculate n indicator weight, and then converting each indicator weight value that obtained by weighting method into the order value of the indicator weight.
2) Calculating Spearman rank correlation coefficient ρ_{ab} between the first a subjective weighting method and the first b objective weighting method by the Eq. (1).

$$\rho_{ab} = 1 - \frac{6\sum_{c=1}^{n}\left(y_{ac} - y_{bc}\right)^2}{n^3 - n} \tag{1}$$

Where, a=1,2, …, p; b=1,2, …, q, y_{ac} is the order value of the first c indicator weight that obtained by the first a subjective weighting method, y_{bc} is the order value of the first c indicator weight that obtained by the first b objective weighting method.
Given the significant level α , the critical valueρ_a can be obtained by referring the Spearman rank correlation coefficient critical value table. If min{ρ_{ab}}≥ρ_a, then it indicates that the degree of consistency between the subjective and objective weighting methods is better, otherwise, we need to adjust the corresponding subjective and objective weighting methods, so as to meet this requirement.
3) Finding out the maximumρ_{uv} in Spearman rank correlation coefficient ρ_{ab}, and ρ_{uv}=max{ρ_{ab}}. Calculate the sum of Spearman rank correlation coefficient of subjective weighting method u and other weighting methods. So does the objective weighting method v . Then compare the sums and select the larger one. Suppose that is

subjective weighting method u , it shows the subjective weighting method u is the highest relative consistency method in all weighting methods. According to the Eq. (1) to calculate the Spearman rank correlation coefficient of subjective weighting method u and other subjective weighting methods, the rank correlation coefficient of the subjective method u with all weighting methods constitute a vector $\rho_u=(\rho_{u1}\ \rho_{u2,\dots,}\rho_{u,p+q})$.

4) Applying normalization processing to ρ_u, the corrected weight vector $\beta=(\beta_{1,}\ \beta_{2,\dots,}\ \beta_{p+q})$ can be obtained. Where,

$$\beta_i=\frac{\rho_{ut}}{\sum_{t=1}^{p+q}\rho_{ut}}\ \left(t=1,2,\cdots,p+q\right) \tag{2}$$

5) Calculating the combination weight ω .

$$\omega=\left(\beta_1,\quad \beta_2,\quad \cdots,\quad \beta_{p+q}\right)\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{p1} & x_{p2} & \cdots & x_{pn} \\ z_{11} & z_{12} & \cdots & z_{1n} \\ \cdots & \cdots & \cdots & \cdots \\ z_{q1} & z_{q2} & \cdots & z_{qn} \end{bmatrix} \tag{3}$$

In which, x_{ac} is the weight of the first c indicator obtained by the first a subjective weighting method, z_{bc} is the weight of the first c indicator that obtained by the first b objective weighting method.

4. Fuzzy TOPSIS of safety culture construction level

The evaluation indicators of safety culture construction level have fuzziness and uncertainty, fuzzy TOPSIS based on triangular fuzzy number can deal with fuzziness of evaluation factor.

4.1 Determine set of program, factor and expert

According to the existing evaluation indicators of safety culture construction level, the evaluation factor set is established. Suppose $A=\{A_1,A_2,\dots,Am\}$ is the program set, $U=\{U_1,U_2,\dots,U_n\}$ is the factor set, $E=\{E_1,E_2,\dots,E_n\}$ is the evaluation expert set.

4.2 Construct fuzzy decision matrix

Let h evaluation experts use the method of language variable assignment for qualitative evaluation indicators in the n evaluation indicators from m programs. Linguistic variable can be represented by triangular fuzzy number, and the transform relationship (Li, 1998) is presented in Table 2. The quantitative indicator values in the evaluation indicator also take the form of triangular fuzzy number, for example, f is expressed as (f, f, f).

Table 2: Transform relationship between linguistic variable and triangular fuzzy number

Linguistic variable	Very poor(VP)	Poor(P)	Fair(F)	Good(G)	Very good(VG)
Triangular fuzzy number	(0,0,0.25)	(0,0.25,0.5)	(0.25,0.5,0.75)	(0.5,0.75,1)	(0.75,1,1)

Suppose the fuzzy value of the indicator U_j of program A_i given by expert E_k is triangular fuzzy number $\tilde{a}_{ij}^{(k)}=\left(l_{ij}^{(k)},\ m_{ij}^{(k)},\ u_{ij}^{(k)}\right)$, the average fuzzy value $\tilde{a}_{ij}=\left(l_{ij},\ m_{ij},\ u_{ij}\right)$ of the indicator U_j of program A_i can be obtained by the Eq. (4).

$$\tilde{a}_{ij}=\frac{1}{h}\sum_{k=1}^{h}\tilde{a}_{ij}^{(k)} \tag{4}$$

Thus, fuzzy decision matrix $\tilde{A}=\left[\tilde{a}_{ij}\right]_{m\times n}$ can be constructed.

4.3 Normalize fuzzy decision matrix

Fuzzy decision matrix $\tilde{A}=\left[\tilde{a}_{ij}\right]_{m\times n}$ can be normalized to $\tilde{V}=\left[\tilde{v}_{ij}\right]_{m\times n}$ by the Eq. (5).

$$\tilde{v}_{ij}=\begin{cases}\left(\dfrac{l_{ij}}{u_j^{\max}},\ \dfrac{m_{ij}}{u_j^{\max}},\ \dfrac{u_{ij}}{u_j^{\max}}\right), & j\in I^{'}\\ \left(\dfrac{l_j^{\min}}{u_{ij}},\ \dfrac{l_j^{\min}}{m_{ij}},\ \dfrac{l_j^{\min}}{l_{ij}}\right), & j\in I^{''}\end{cases} \tag{5}$$

In which, $u_j^{\max}=\max\left\{u_{ij}\mid u_{ij}\in\tilde{a}_{ij}\right\}$, $l_j^{\min}=\min\left\{l_{ij}\mid l_{ij}\in\tilde{a}_{ij}\right\}$, $I^{'}$ is benefit-type indicator, $I^{''}$ is cost-type indicator.

4.4 Construct weighted normalized fuzzy decision matrix
Considering the different importance values ω_j of each factor, the weighted normalized fuzzy decision matrix $\tilde{R}=\left[\tilde{r}_{ij}\right]_{m\times n}$ can be constructed by the equation below:

$$\tilde{r}_{ij}=\omega_j\tilde{v}_{ij} \tag{6}$$

4.5 Determine positive and negative ideal solution
Identify the fuzzy positive ideal solution $\tilde{r}^{+}=\left(\tilde{r}_1^{+},\ \tilde{r}_2^{+},\ \cdots,\ \tilde{r}_n^{+}\right)$ and the fuzzy negative ideal solution $\tilde{r}^{-}=\left(\tilde{r}_1^{-},\ \tilde{r}_2^{-},\ \cdots,\ \tilde{r}_n^{-}\right)$, where $\tilde{r}_j^{+}=\max_i \tilde{r}_{ij}, \tilde{r}_j^{-}=\min_i \tilde{r}_{ij}$.

4.6 Calculate distance of each program from positive and negative ideal solution
Using the distance formula of triangular fuzzy number(Chen, 2000), the distance of each program from fuzzy positive ideal solution and fuzzy negative ideal solution can be calculated respectively by using:

$$D_i^{+}=\sum_{j=1}^{n} d\left(\tilde{r}_j^{+},\ \tilde{r}_{ij}\right) \tag{7}$$

$$D_i^{-}=\sum_{j=1}^{n} d\left(\tilde{r}_j^{-},\ \tilde{r}_{ij}\right) \tag{8}$$

4.7 Calculate closeness coefficient of each program
The closeness coefficient of each program can be calculated by the Eq. (9).

$$T_i=\frac{D_i^{-}}{D_i^{+}+D_i^{-}} \tag{9}$$

According to the closeness coefficient T_i of each program, we can sort the programs. The greater the closeness coefficient, the better the program is.

5. Example analyses

Filing in four companies ($A_{1\text{-}4}$) in China which have declared " Beijing safety culture demonstration enterprises" in 2013 as an example, safety culture construction level of four companies are evaluated by using the above methods. The evaluation indicators ($U_{1\text{-}9}$) are shown in table 1. The original evaluation information is provided by five experts ($E_{1\text{-}5}$).

5.1 Determination of Indicator Weight
The subjective weighting method is improved AHP (Qin and Li, 2002) and triangular fuzzy number weighting method (Zhang, 2015); objective weighting method is entropy method (Zhou et al., 2007). According to the Eq. (1), the Spearman rank correlation coefficient between the objective and subjective weighting methods is ρ_{11}=0.95, ρ_{21}=0.7. Significance level is set to α=0.05, then min{ρ_{ab}}=0.7≥ρ_a=0.6, consistency of subjective and objective weighting method is better.
The maximum of rank correlation coefficient is max{p_{ab}}=0.95, namely, the consistency between improved AHP and entropy method is best. Comparing the rank correlation coefficient of these two methods and the triangular fuzzy number weighting method, it is concluded that the relative consistency of improved AHP is the best. After normalizing the vector that consists of the Spearman rank correlation coefficient between improved AHP and all weighting methods, the modified weight vector β=(0.373, 0.273, 0.354) can be obtained. According to the Eq. (3), combination weight vector of evaluation indicator is obtained, that is ω=(0.156, 0.130, 0.085, 0.105, 0.115, 0.096, 0.090, 0.083, 0.140).

5.2 Calculation Process of Fuzzy TOPSIS

Five experts express their opinions on the ratings of each company with respect to the nine indicators independently. Table 3 shows the original evaluation information provided by five experts.

Table 3: Ratings of four companies with respect to nine indicators by the five experts

Expert	Company	U1	U2	U3	U4	U5	U6	U7	U8	U9
E1	A	VG	VG	0.912	G	G	G	G	VG	G
	B	F	G	0.553	F	F	F	G	F	G
	C	G	G	0.726	G	G	G	G	G	VG
	D	G	VG	0.758	G	G	G	G	F	VG
E2	A	G	VG	0.912	G	F	VG	G	G	G
	B	F	P	0.553	F	F	P	F	G	G
	C	VG	G	0.726	G	VG	G	G	G	G
	D	G	G	0.758	VG	G	G	G	G	VG
E3	A	F	G	0.912	VG	VG	G	G	G	G
	B	VP	F	0.553	F	F	P	F	VG	F
	C	F	G	0.726	G	G	F	G	G	G
	D	F	VG	0.758	G	VG	F	VG	F	G
E4	A	VG	VG	0.912	G	F	G	G	VG	VG
	B	F	F	0.553	G	F	F	G	G	F
	C	G	VG	0.726	G	VG	G	VG	G	G
	D	VG	G	0.758	G	VG	G	VG	G	G
E5	A	G	VG	0.912	VG	VG	G	VG	G	G
	B	F	P	0.553	F	G	F	F	G	F
	C	G	G	0.726	G	G	G	G	F	VG
	D	VG	VG	0.758	G	G	G	G	G	F

Then, linguistic values change to triangular fuzzy number and quantitative indicator values take the form of triangular fuzzy number. By Eqs. (4), (5) and (6), weighted normalized fuzzy decision matrix $\tilde{R}$ is constructed.

$$\tilde{R}=\begin{bmatrix}(0.090,0.131,0.156) & (0.033,0.066,0.107) & (0.082,0.123,0.156) & (0.903,0.131,0.156)\\ (0.091,0.124,0.130) & (0.026,0.059,0.091) & (0.072,0.104,0.130) & (0.085,0.117,0.130)\\ (0.085,0.085,0.085) & (0.052,0.052,0.052) & (0.068,0.068,0.068) & (0.071,0.071,0.071)\\ (0.063,0.089,0.105) & (0.032,0.058,0.084) & (0.053,0.079,0.105) & (0.058,0.084,0.105)\\ (0.058,0.086,0.104) & (0.035,0.063,0.092) & (0.069,0.098,0.115) & (0.069,0.098,0.115)\\ (0.053,0.077,0.096) & (0.014,0.038,0.062) & (0.043,0.067,0.091) & (0.043,0.067,0.091)\\ (0.050,0.072,0.090) & (0.032,0.054,0.077) & (0.050,0.072,0.090) & (0.054,0.077,0.090)\\ (0.050,0.071,0.083) & (0.042,0.062,0.079) & (0.037,0.058,0.079) & (0.033,0.054,0.075)\\ (0.077,0.112,0.140) & (0.049,0.084,0.119) & (0.084,0.119,0.140) & (0.077,0.112,0.133)\end{bmatrix}^T$$

Identify the fuzzy positive ideal solution and the fuzzy negative ideal solution.

$$\tilde{r}^{+}=\big((0.090,0.131,0.156),\ (0.091,0.124,0.130),\ (0.085,0.085,0.085),\ (0.063,0.089,0.105),\ (0.058,0.086,0.104),\ (0.053,0.077,0.096),\ (0.054,0.077,0.090),\ (0.050,0.071,0.083),\ (0.084,0.119,0.140)\big)$$

$$\tilde{r}^{-}=\big((0.033,0.066,0.107),\ (0.026,0.059,0.091),\ (0.052,0.052,0.052),\ (0.032,0.058,0.084),\ (0.035,0.063,0.092),\ (0.014,0.038,0.062),\ (0.032,0.054,0.077),\ (0.033,0.054,0.075),\ (0.049,0.084,0.119)\big)$$

Using the Eq. (7) (8) and (9) to calculate the closeness coefficient of four companies, they are T_1=0.933, T_2=0.023, T_3=0.775, T_4=0.828. The sort of safety culture construction level of four companies is $A_1>A_4>A_3>A_2$, that is, company A_1 is best, company A_4 and company A_3 followed by, company A_2 is worst. The results are consistent with selection result of Beijing safety culture demonstration enterprise. Therefore, fuzzy TOPSIS method can effectively achieve the sort of enterprise safety culture construction level.

6. Conclusions

By using the combination of objective and subjective weighting methods based on Spearman rank correlation coefficient to overcome the shortcomings of a single objective or subjective weighting method, the evaluation indicator weight of safety culture construction level is more reasonable. Taking four companies in China as examples, using the fuzzy TOPSIS to evaluate safety culture construction level, research shows that the results are consistent with selection result of Beijing safety culture demonstration enterprise. So this method can evaluate the construction level of enterprise safety culture effectively.

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