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RESEARCH ARTICLE

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Reliability analysis of urban gas transmission and distribution system based on FMEA and correlation operator

Abstract In order to improve the safety management of urban gas transmission and distribution system, failure mode and effects analysis (FMEA) was used to construct the reliability analysis system of the pipeline network. To solve the problem of subjectivity and uncertainty of the multi-expert decision making, the correlation operator was introduced into the calculation of the risk priority number (RPN). Using FMEA along with weight analysis and expert investigation approach, the FMEA evaluation table was given, including five failure modes, risk priority numbers, failure causes and effects, as well as corrective actions. The results show that correlation operator can directly process the linguistic terms and quantify the priority of the risks.

Keywords gas transmission and distribution system, risk evaluation, reliability analysis, failure mode and effects analysis (FMEA), correlation operator

1 Introduction

The transmission and distribution pipeline network plays an indispensable role in urban gas supply systems, and serves as a bridge for communications between gas sources and users. On account of the damages of corrosion, design defect, ground activity, etc., the pipeline perforation, leakage and even fracture happen easily in the transmission and distribution system, triggering fire, explosion and others accidents. In recent years, with the rapid increase of gas supplies and the fast expansion of pipeline network coverage, great attention has been paid to the reliability analysis of urban gas pipeline network [1]. Failure mode and effects analysis (FMEA) is one of the most widely used reliability analysis methods in engineering application. The objective of FMEA is to define, identify and eliminate known and/or potential failures, problems, errors, etc. from the system, design, process, and/or service. FMEA was first applied in 1950s by U.S. aviation. Now, it has been widely used in industrial design and prevention activities in manufacturing process including aerospace, machinery, electricity, vehicles, etc. It is regarded as an effective reliability analysis technique and worth spreading [2].

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In actual engineering application, FMEA usually employs a risk priority number (RPN) to evaluate the risk level of the product and the process, which is the product of the occurrence (O), severity (S), and detection (D). That is

$$\mathrm{RPN} = O \times S \times D, \tag{1}$$

where O is the chance of the failure, S is the severity of the failure to the customers, and D is the chance of not detecting the failure before delivery. Nevertheless, there mainly exist some problems in the traditional FMEA in the following areas: ① Traditional RPN neglects the relative importance among O, S and D. ② Different combinations of O, S and D may produce exactly the same value of RPN, but their hidden risk implications may be totally different. ③ The three factors are difficult to be precisely estimated because of linguistic indeterminacy and subjectivity.

To overcome the above drawbacks, various modified FMEA methods have been proposed by domestic and overseas scholars. Those methods can be divided into five main categories, which are multi-criteria decision-making (MCDM), mathematical programming (MP), artificial intelligence (AI), hybrid approaches and others [3]. Franceschini and Galetto [4] presented a multi-expert MCDM (ME-MCDM) technique to calculate the RPN in FMEA. The method provided each decision-making criterion an expansion fuzzy evaluation set. If two or more failure modes have the same RPNs, a more detailed selection was provided to discriminate their relative ranking. Chang et al. [5] used fuzzy method and grey theory for FMEA, where the fuzzy set theory was adopted to establish fuzzy linguistic terminology to evaluate the failure mode and the corresponding fuzzy number, and grey relational theory was applied to determine the risk priority of potential causes. Wang et al. [6] introduced fuzzy weighted geometric means into the calculation process of the RPNs, in which triangular fuzzy number and trapezoidal fuzzy number were used to conduct risk factors and relative weights respectively.

Fuzzy logic has been extensively applied in modified FMEA researches. The method is able to deal with the uncertain information in the analysis process correctly to decrease the subjective effect of expect decision making. Nevertheless, secondary calculation in which fuzzy theory transforms linguistic terms into fuzzy number first and then defuzzifies it back will cause the decision-making information loss. This paper introduces the correlation operator to simplify the secondary calculation process, directly conduct the correlation calculation of linguistic terms, and, furthermore, conduct reliability analysis and evaluation of gas transmission and distribution system based on FMEA.

2 Failure mode and effect analysis (FMEA) and correlation operator

2.1 Establishment of FMEA

2.1.1 Potential failure modes, failure causes and effects

The so-called failure mode is defined as the manner in which a system, design, process, service or subsystem could potentially fail to meet the design intent and function so as to cause problems and faults. A failure can be known or potential. FMEA is a kind of beforehand activity. During the implementation process, FMEA detects potential failure by analyzing functional defect, thus taking a proactive role in potential failure [7].

2.1.2 Risk factors grading and expert investigation

There are mainly two kinds of grade classifications on risk factors in industry, grade classification based on 5-point scale and grade classification based on 10-point scale. The latter is widely used for its high accuracy. Attribute evaluation values are usually obtained from multi-expert decision-making. Based on the known RPNs of all failure modes, the relationship among relative risk of failure modes can be obtained [8].

2.1.3 Risk control: corrective action

Risk control is an important component in risk management systems. In actual implementation, correlative corrective actions aiming at each failure mode that may cause faults in engineering projects should be proposed to improve the project security and reliability [9].

2.1.4 FMEA tracking

FMEA is a systematic persistent reliability assessment method. The dynamic characteristic demands that after taking some corrective actions to reduce the system risk, the FMEA team is supposed to evaluate the failure mode again, calculate the new RPN and ensure that the risk leading failure is really mitigated. The procedure may repeat many times until the risks has been eliminated or has been reduced to an acceptable level based on existing technology [10].

2.2 Correlation operator (CLOWG)

2.2.1 Preliminary knowledge: linguistic information decision-making

Due to the complexity and the vagueness of objective things, evaluation information is always expressed in a linguistic way in the decision-making process. In order to quantifying the linguistic terms during the process of measurement, decision makers need to establish adequate linguistic evaluation scale to provide the basis of the decision-making linguistic terms. The linguistic evaluation scale is defined as

$$S = \{s_i | i = 1,2,\cdots,t\}, \tag{2}$$

The potential of the set is t–1. S should satisfy the following conditions [11]:

1) If $i > j$, then $s_i > s_j$;

2) Inverse operations exist, that is $\text{rev}(s_i) = s_j$making$i+$ $+j = t+1$;

3) If $s_i > s_j$, then $\max(s_i, s_j) = s_i$;

4) If $s_i < s_j$, then $\max(s_i, s_j) = s_j$.

For simple calculating and avoiding decision information loss, an expanding continuous linguistic evaluation scale set $\overline{S}$ should be established on the former discrete linguistic evaluation scale set S, that is $S = \{s_i | i = 1,2,3,\ldots,t\}$, $\overline{S} = \{s_\alpha | \alpha \in [1,N]\}$, where $N(N \geqslant t)$ is a sufficiently large natural number. If $i \in \{1,2,\ldots,t\}$, then s_i is a source term; if $s_i \in \overline{S}$, and $s_i \cap S$ is an empty set, then s_i is a virtual term. Generally, source terms are used to evaluate the decision information and virtual terms usually exist in calculation [12].

Definition 1: $\omega = [\omega_1,\omega_2,\ldots,\omega_n]^{\mathrm{T}}$, where ω is an exponential weighted vector, satisfying $\omega_j \in [0,1]$, $\sum_{j=1}^{n} \omega_j = 1$, then a n-dimensional linguistic ordered weighted geometric (LOWG) mean operator is defined as

$\overline{S}^n \rightarrow \overline{S}$:

$$\begin{aligned}&\mathrm{LOWG}_{\omega}(s_1,s_2,\ldots,s_n)\\&=(s_{k(1)})^{\omega_1}\times(s_{k(2)})^{\omega_2}\times\cdots\times(s_{k(n)})^{\omega_n},\end{aligned} \tag{3}$$

$s_{k(j)}$ is the j-th largest element in the linguistic terms set $S=\{s_i|i=1,2,\ldots,t\}$ [13].

2.2.2 Correlation operator

In practical engineering problems, expert group decisions are always subjective and random so that higher or lower evaluations likely occur, affecting the accuracy of decision information. To solve this problem, this paper makes correlation analysis between one certain term and the term group it belongs to. The decision information which has a larger divergence is amended by giving a lighter weight so as to optimize information processing.

Definition 2: Let S be a group linguistic terms set (linguistic evaluation) consisting of $s_1,s_2,\cdots s_n$, in which $s_j\in S(j=1,2,\ldots,n)$, then the mean value of the linguistic terms is defined as

$$S_{\mu}=\frac{1}{n}(s_1+s_2+\cdots+s_n). \tag{4}$$

Definition 3: Let S be a group linguistic terms set (linguistic evaluation) consisting of $s_1,s_2,\ldots,s_n$ and s_{μ} is the mean value of the linguistic terms, then the potential residual of the linguistic terms is defined as

$$R(s_j,\ s_{\mu})=\frac{|s_j-s_{\mu}|}{n-1}. \tag{5}$$

Definition 4: Let S be a group linguistic terms set (linguistic evaluation) consisting of $s_1,s_2,\ldots,s_n$, and s_{μ} is the mean value of the linguistic terms. If the subscripts $(1,2,\ldots,n)$ are replaced to $\left(\sigma(1),\sigma(2),\ldots,\sigma(n),\right)$ making $s_{\sigma(j-1)}\geqslant s_{\sigma(j)}$ is satisfied for any $j=1,2,\ldots,n$, then the correlation degree between the j-th largest linguistic term $s_{\sigma(j)}$ and the mean value of the linguistic term set s_{μ} is described as

$$C\left(s_{\sigma(j)},\ s_{\mu}\right)=1-\frac{R^2\left(s_{\sigma(j)},\ s_{\mu}\right)}{\sum_{j=1}^{n}R^2\left(s_{\sigma(j)},\ s_{\mu}\right)}. \tag{6}$$

Let $\omega=[\omega_1,\omega_2,\ldots,\omega_n]^{\mathrm{T}}$ be a weighted value set of expert group decision. Then ω_j is defined as

$$\omega_j=\frac{C\left(s_{\sigma(j)},\ s_{\mu}\right)}{\sum_{j=1}^{n}C\left(s_{\sigma(j)},\ s_{\mu}\right)}, \tag{7}$$

where $\omega_j\in[0,1],\sum_{j=1}^{n}\omega_j=1$, then according to Eq. (3), the CLOWG operator based on the correlation analysis is defined as

$$\begin{aligned}&\mathrm{CLOWG}_{\omega}(s_1,s_2,\ldots,s_n)\\&=s_{\sigma(1)}^{C\left(s_{\sigma(1)},s_{\mu}\right)/\sum_{j=1}^{n}C\left(s_{\sigma(j)},s_{\mu}\right)}\\&\times s_{\sigma(2)}^{C\left(s_{\sigma(2)},s_{\mu}\right)/\sum_{j=1}^{n}C\left(s_{\sigma(j)},s_{\mu}\right)}\\&\times\cdots\times s_{\sigma(n)}^{C\left(s_{\sigma(n)},s_{\mu}\right)/\sum_{j=1}^{n}C\left(s_{\sigma(j)},s_{\mu}\right)}.\end{aligned} \tag{8}$$

Due to the fact that

$$\sum_{j=1}^{n}C\left(s_{\sigma(j)},s_{\mu}\right)=\sum_{j=1}^{n}C(s_j,s_{\mu}).$$

Eq. (8) can, therefore, be rewritten as

$$\begin{aligned}&\mathrm{CLOWG}_{\omega}(s_1,s_2,\ldots,s_n)\\&=s_1^{C(s_1,s_{\mu})/\sum_{j=1}^{n}C(s_j,s_{\mu})}\\&\times s_2^{C(s_2,s_{\mu})/\sum_{j=1}^{n}C(s_j,s_{\mu})}\\&\times\cdots\times s_n^{C(s_n,s_{\mu})/\sum_{j=1}^{n}C(s_j,s_{\mu})}.\end{aligned} \tag{9}$$

Equation (9) shows that the set of CLOWG operators has nothing to do with the sequence of linguistic terms, therefore, evaluation values do not have to be sorted or be assigned weighted vector separately. The CLOWG operator has the features of simple calculation and better engineering applicability.

3 Reliability analysis of urban gas transmission and distribution system

An urban gas transmission and distribution system consists of the main network system and secondary network systems. The main network system has the functions of gas reception, gas transmission, gas storage, peak shaving, etc. The secondary network systems transport the gas from the main network system to users.

1) Establish three-dimensional linguistic evaluation

Table 1 Evaluation of risk factors of failure modes

Rating	Probability of occurrence	Severity of a failure	Detection of a failure
10	Almost certain	Hazardous	Almost impossible
9	Very high	Serious	Remote
8	High	Extreme	Very slight
7	Moderately high	Major	Slight
6	Medium	Significant	Low
5	Low	Moderate	Medium
4	Slight	Minor	Moderately high
3	Very slight	Slight	High
2	Remote	Very slight	Very high
1	Almost never	No	Almost certain

scale set $\boldsymbol{S}=(O,S,D)^{\mathrm{T}}$. The three risk factors are evaluated using the 10-scale described in Table 1.

2) Determine failure modes and expert investigation method. In this system, evaluation objects are defined as pipelines and accessories. Failure modes can be summed up in 5 types, which are pipeline leakage (M_1), pipeline break (M_2), valve leakage (M_3), filter failure (M_4) and dispersing pipe leakage (M_5). Expert group decision-making evaluation is listed in Table 2.

3) Property weight. According to analytic hierarchy process (AHP) [14–15], the property weight of O, S and D are determined as $\omega=[0.316,0.473,0.211]$. The evaluation value of expert i on the failure mode $j(F_{ji})$ can be calculated. The evaluation values are tabulated in Table 3.

4) Expert weight. Expert opinions have different weights because of their different domain of knowledge and expertise. Expert opinion weight on the 5 failure modes can be calculated with Eqs. (4)–(7). The weight values are summarized in Table 4.

5) RPN. The RPN of the failure modes from expert group decision-making are calculated with Eq. (9). The results are presented in Table 5.

Therefore, the risk priority sequence of failure modes is $M_1>M_2>M_3>M_5>M_4$.

6) The risk evaluation table of urban gas transmission and distribution system based on FMEA and CLOWG operator is given in Table 6.

4 Conclusions

To increasing the accuracy of the reliability analysis based on FMEA, this paper proposed correlation operator based on the linguistic information decision-making theory and correlation analysis. During the process of introducing RPN of FMEA in the instance, the results are as follows:

1) Establishment of linguistic term scale to quantify the decision-making information effectively indicates the

Table 2 Expert group decision-making property evaluation information

	M_1	M_2	M_3	M_4	M_5
Expert 1	(8, 6, 2)	(7, 10, 1)	(8, 2, 3)	(3, 4, 5)	(4, 3, 4)
Expert 2	(7, 6, 3)	(5, 8, 2)	(7, 4, 4)	(4, 6, 5)	(3, 5, 4)
Expert 3	(7, 8, 4)	(5, 7, 2)	(6, 4, 5)	(5, 3, 6)	(3, 4, 5)
Expert 4	(8, 7, 2)	(4, 8, 2)	(6, 5, 3)	(3, 3, 5)	(4, 4, 6)
Expert 5	(7, 6, 3)	(6, 8, 2)	(9, 4, 4)	(3, 4, 6)	(4,5,5)

Table 3 Expert group decision-making evaluation value

	M_1	M_2	M_3	M_4	M_5
Expert 1	5.21	5.50	3.38	3.82	3.49
Expert 2	5.44	5.15	4.77	5.10	4.06
Expert 3	6.63	4.84	4.77	4.09	3.83
Expert 4	5.61	4.79	4.75	3.34	4.36
Expert 5	5.44	5.45	5.17	3.97	4.66

Table 4 Expert weight information

	M_1	M_2	M_3	M_4	M_5
Expert 1	0.208147	0.179408	0.062877	0.241584	0.145018
Expert 2	0.239891	0.249997	0.244418	0.08981	0.249877
Expert 3	0.062799	0.19403	0.244831	0.249944	0.23093
Expert 4	0.249272	0.180645	0.245372	0.169729	0.2265
Expert 5	0.239891	0.19592	0.202501	0.248932	0.147675

Table 5 RPN of failure modes

	M_1	M_2	M_3	M_4	M_5
RPN	5.50	5.14	4.74	3.94	4.06

Table 6 Risk evaluation table

Evaluation object	Failure mode	Failure cause	Failure effect	Corrective action	RPN
Pipeline	Pipeline leakage	Internal and external corrosion; a third-party damage; welding defect; violation of construction procedure; material defect	Leaking gas and accumulating gas in part; causing accidents such as poisoning, fire, explosion, etc. when problems get more serious	Corrosion prevention: adopting external corrosion protection combined with cathode protection; reducing corrosive medium in gas; strengthening the construction of safe operation on the ground	5.50
	Pipeline break	A third-party damage; welding defect; internal and external corrosion	Damaging pipeline; accumulating gas in part; causing accidents such as poisoning, fire, explosion, etc. when seriously	Increasing scrutiny on the municipal engineering construction nearby underground gas pipeline to prevent damaging gas pipeline; enhancing the quality management of construction	5.14
Accessory	Valve leakage	Internal component damage; valve blocking; valve corrosion	Poor sealing, forming leak point; affecting pipeline access road open and close; affecting the regulation of pipeline flow	Replacing with valve body of high mechanical strength; adopting tight and durable sealing elements; adopting elements with high corrosion resistance to transmission medium	4.74
	Dispersing pipe leakage	Dispersing pipe corrosion; dispersing pipe physical damage	Forming mixed explosive gas in pipeline; damaging downstream equipment and pipeline	Adopting corrosion prevention on equipment; trouble shooting all factors of physical damage	4.06
	Filter failure	Filter element damage; sewage drain blocking	Damaging internal parts of equipment; affecting the sealing of valve, pressure regulator and safety device; affecting accuracy of pressure regulator, flowmeter and other instruments	Examine damaged condition of all elements of filter; replacing elements with good performance; periodically cleaning sewage drain to prevent blocking	3.94

ambiguity of expert decision-making and avoids the loss of decision information. Correlation operator indicates the degree of correlation between research term and the term group it belongs to. In the application of FMEA, the fairness of decision information and the accuracy of linguistic evaluation are improved by determining weights with the help of correlation operator.

2) Based on FMEA analysis of one urban gas transmission and distribution system, this paper considers risk property weights and expert opinion weights and verifies flexibility, practicability and effectiveness of the method.

3) This paper quantitatively presents the risk priority of 5 failure modes of the transmission and distribution system, and systematically analyzes the cause of failure and corresponding corrective actions, which improves the reliability of evaluation, helps relevant technical staff to make risk management decisions, and promotes the development of risk management and comprehensive evaluation of the urban gas.

References

1. Duan C G. Gas Transmission and Distribution. Beijing: China Architecture & Building Press, 2011, 68–99
2. Stamatics D H (USA). Failure Mode and Effect Analysis: FMEA from Theory to Execution. 2nd Edition. Translated by Chen X T, Yao S H. Beijing: National Defence Industry Press, 2005, 36–67 (in Chinese)
3. Liu H C, Liu L, Liu N. Risk evaluation approaches in failure mode and effects analysis: a literature review. Experts Systems with Applications, 2013, 40(2): 828–838
4. Franceschini F, Galetto M. A new approach for evaluation of risk priorities of failure modes in FMEA. International Journal of Production Research, 2001, 39(13): 2991–3002
5. Chang C L, Wei C C, Lee Y H. Failure mode and effects analysis using fuzzy method and grey theory. Kybernetes, 1999, 28(9):1072–1080
6. Wang Y M, Chin K S, Poon G K K, Yang J B. Risk evaluation in failure mode and effects analysis using fuzzy weighted geometric mean. Expert Systems with Applications, 2009, 36(2): 1195–1207
7. Pyzdek T. The Six Sigma Project Planner. McGraw-Hill Trade, 2003, 100–111
8. Li Y J, Yu J X. Quality risk analysis of submarine pipeline in construction period base on FMEA and fuzzy theory. China Safety Science Journal, 2012, 22(1): 112–117 (in Chinese)
9. McDermott R E, Mikulak R J, Beauregard M R. The Basics of FMEA. 2nd Edition. Productivity Press, 2008, 23–38
10. Zheng J J, Zhang Q L, Wang X M, Wang X L. FMEA analysis of backfilling pipeline system and fuzzy evaluation of failure effects. China Safety Science Journal, 2009, 19 (6): 166–171 (in Chinese)
11. Wei G W. Method of uncertain linguistic multiple attribute group decision making based on dependent aggregation operators. Journal of Systems Engineering and Electronics, 2010, 32(4): 764–769 (in Chinese)
12. Xu Z S. On method of multi-attribute group decision making under pure linguistic information. Control and Decision, 2004, 19(7): 778–781 (in Chinese)