Improved Fuzzy Evaluation Model Analysis of Nuclear Power Plant Operational Safety Performance

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Abstract
The evaluation on nuclear power plant operational safety performance had great significance on whether the nuclear power plant operated safely or not. Currently the academic literatures on nuclear power plant operational safety performance are rare. Improved Fuzzy evaluation model which introduce confidence level had been used into the evaluation of nuclear power plant operational safety performance. The article built safety performance indicator system and further established importance level evaluation matrix which showed the indexes relative importance, and established performance evaluation matrix which represented indicators impact on operational effect. From the importance level evaluation matrix the weigh and confidence of indicators can be gained and from the performance evaluation matrix the evaluation matrix can be gained. The preliminary evaluation result and synthetic confidence can be obtained by multiplying evaluation matrix by indicator weigh and confidence, and then the final evaluation result can be achieved.

Keywords: nuclear power plant, safety performance indicator, confidence level, fuzzy evaluation model

1. Introduction
In the present era which the energy is extremely used, nuclear safety has been a controversial topic in energy field. From the Three Mile Island in the USA to the Chernobyl disaster in the Former Soviet Union and the Japan's Fukushima nuclear leak event, an increasing number of people have realized that the safety performance of the nuclear power station not only represent the enterprise's science and technology level, but also has a significant influence in our county's polity, economy and livelihoods. Therefore, to evaluate the operational safety performance of nuclear power station is not so much to meet the need as to be compelled by situation.

The evaluation of nuclear program in our county mainly concentrates on program's environment, economy, supply or technology, but rarely in the operational safety performance. To fill in the blank, the article will establish safety performance indicator system (SPIs), and evaluate nuclear program safety operation state through analyzing the indicators' importance and influence.

2. Determination of Nuclear Program Operation SPIs
The international existing nuclear operational performance indicator system has three types: the SPIs developed and applied by *International Atomic Energy Agency* (IAEA), the SPIs published by *World Association of Nuclear Operators* (WANO) and the SPIs generalized and executed by *Nuclear Regulatory Commission* (NRC).

The SPIs developed by IAEA is a pyramid structure which takes operational safety performance into consideration [1]. The SPIs is gradually detailed from the top to the bottom. The top level is operational security attributes; the second level is global level parameter; the third level is practical parameter and the parameters in the last level can be supervised and measured directly. The SPIs of IAEA is comprehensively and systematically, but still short of pertinence and practicability.

The NRC's SPIs can be separated into three sectors: reactor safety performance, radiation security, disaster prevention and protection [2]. The supervision result can be

combined with performance indicator by NRC, and the emphasis will be put on the part with higher risk in order to realize the balance between risk and benefit. Besides, in order to realize experience exchangement and build a unified operational performance evaluation criterion, WANO released a report about operational safety performance indicator in 1991 and gradually established a fairly complete set of indicator system [3].

On the basis of the three indicator system, the article will synthesize and induce to obtain a new SPIs as shown in Figure 1.
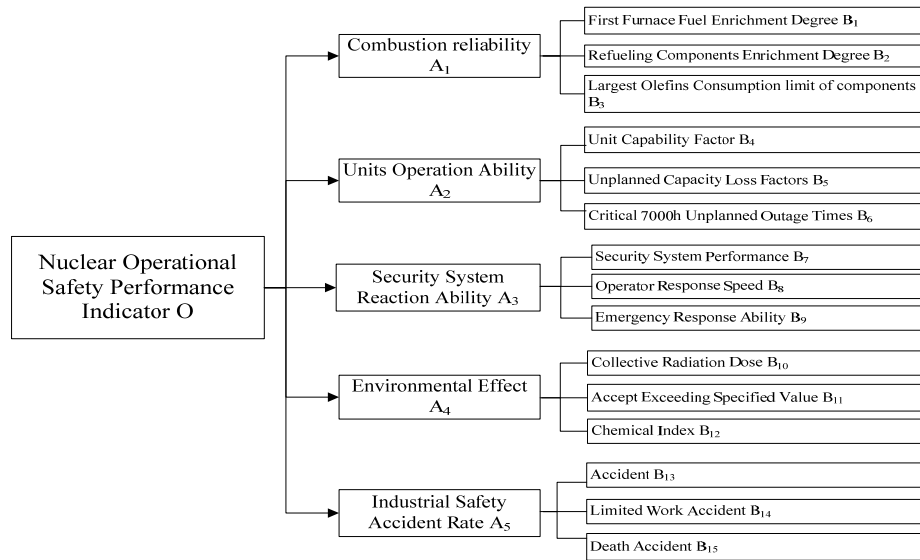
Figure 1. Nuclear Operational Safety Performance Indicator System

3. Fuzzy Synthetic Evaluation Model Based on Confidence Level
3.1. Model Introduction

The fuzzy evaluation model is one of the most frequently-used evaluation methods applied in programmer evaluation, the main idea of which is to build evaluation matrix by Membership Functions or Delphi method, and the matrix should be compounded with index weight which can be obtained by *Analytic Hierarchy Process* (AHP). Finally the result can be gained after stepwise calculation. Fuzzy evaluation model lays emphasis on objectivity and scientificity. In order to realize this purpose, confidence level will be introduced into this model and the result's reliability can be guaranteed via confidence analysis.

3.2. Model Application Procedure

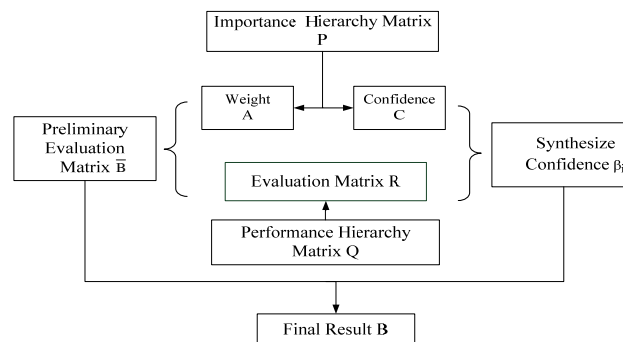The Figure 2 below shows the evaluation processing procedure of the model:

Figure 2. Model Evaluation Procedure

From the figure above, the first thing to do is to establish the importance hierarchy matrix P and the performance evaluation hierarchy matrix Q. Suppose the number of experts is k, and those experts are required to evaluate the importance of every indicator by voting. Count the votes and the matrix P can be obtained by normalization processing. Further, index weight A and confidence C can be calculated from the matrix P via data processing. In addition, according to experts' evaluation on nuclear operational safety indicators, the matrix Q and R also can be obtained. Finally, the evaluation result B can be gained through multiplying preliminary evaluation matrix $\bar{B}$ by synthetic confidence b_i.

3.2.1. Importance Hierarchy Matrix
The importance level of each index is not identical. The indicator which is more important also has greater credibility. Therefore, the confidence of each indicator can be determined by establishing importance hierarchy matrix to increase the objectivity and credibility of the evaluation results.

According to the indicator system in section 1, the index set can be regarded as $U = \{u_1, u_2, \cdots, u_n\}$. Suppose the importance hierarchy is divided into N levels, and the importance degree decreases from level 1 to level N. The experts should evaluate the importance level of every indicators in the set and make a sign at the appropriate level in Table 1 below.

Table 1. Importance Hierarchy Evaluation by No.k expert

Indicator	Importance level (t=1,2,…,k) (level decreasing)			
	t_1	t_2	…	t_N
u_1				
u_2				
…				
u_n				

As revealed above, the votes by every expert are shown in the table. Counting all votes of all experts, the statistic table can be obtained. After processing the data in the statistic table, the importance hierarchy matrix P in the Figure 2 can be determined, and then the weight vector A and confidence vector C also can be obtained.

3.2.2. Matrix Operational Safety Performance Evaluation Matrix
Different indicators have different influence in operational safety performance of nuclear power plant, requiring expert group to evaluate the impact of each indicator. Therefore, the comment set should be the first to be established, viz, $V = \{\text{Excellent}, \text{Good}, \cdots, \text{Poor}\}$.

Table 2. Operational Safety Performance Evaluation

Indicator	Operational Performance Hierarchy			
	Excellent	Good	…	Poor
u_1				
u_2				
…				
u_n				

Firstly, the experts should make a sign in the Table 2 under the appropriate level according to the operational safety impact hierarchy. Then all the votes will be aggregated into a statistic table so that to establish the evaluation matrix *R* after data normalization processing.

3.2.3. Building of Calculating Mode
Above provides the data needed for the evaluation, the following will be the specific steps to establish the model:
(1) Determination of Confidence Vector

The Table 1 can provide the data needed, from which the importance hierarchy matrix $P = \left(\dfrac{p_{i1}}{k}, \dfrac{p_{i2}}{k}, \cdots, \dfrac{p_{im}}{k} \right)$ can be obtained by normalization processing. Assuming the level of matrix takes N, and the evaluation interval [0, 1] can be divided into N portion, then the importance hierarchy evaluation interval is $\left[a_i, b_i \right] = \left[\dfrac{N-i}{N}, \dfrac{N-i+1}{N} \right] (i = 1, 2, \cdots N)$, the interval $\left[a^j, b^j \right]$ can be defined using the following formula:

$$\sum_{i=1}^{N} \frac{p_{ij}}{k} \left[a_i, b_i \right] \square \left[a^j, b^j \right] \tag{1}$$

In the formula above, p_{ij} is the vote of indicator u_j on the interval $\left[a_i, b_i \right]$. Let $z_j = \dfrac{1}{2} \left(a^j + b^j \right)$, then the weight vector $A = \left(a_1, a_2, \cdots, a_j \right)$ can be determined by normalization processing of z_j. If $z_j \hat{I} \left[a_i, b_i \right]$, the confidence of indicator u_j can be determined as $c_j = \dfrac{p_{ij}}{k} (j = 1, 2, \cdots, n)$, and thus to obtain confidence vector $C = \left(c_1, c_2, \cdots, c_j \right)$.

(2) Confidence Analysis

If the evaluation matrix $R = \begin{bmatrix} r_{11} & \cdots & r_{1j} \\ \vdots & \ddots & \vdots \\ r_{i1} & \cdots & r_{ij} \end{bmatrix}$ is known, the confidence vector $C = \left(c_1, c_2, \cdots, c_j \right)$ should be synthesized with the matrix R, and the confidence synthetic formula is as followed:

$$b_i = e_i \max \left\{ q_{1i}, q_{2i}, \cdots, q_{ni} \right\} + \frac{1}{n} \left(1 - e_i \right) \sum_{j=1}^{n} q_{ji}, i = 1, 2, \cdots, m \tag{2}$$

And,

$$q_{ji} = e_j \min \left\{ c_j, r_{ji} \right\} + \left(1 - e_j \right) \left(c_j + r_{ji} \right) / 2, j = 1, 2, \cdots, \text{n} \tag{3}$$

In the formula (2) and (3), the value of e_i is $e_i = \min \left\{ q_{1i}, q_{2i}, \cdots, q_{ni} \right\}$ and the value of e_j is $e_j = \min \left\{ c_j, r_{ji} \right\}$. The preliminary evaluation matrix $\overline{B} = AR$ is known, and then the final evaluation result B can be determined by synthesizing b_i with $\overline{B}$. Lastly, the operational safety performance evaluation hierarchy can be determined according to the maximum membership degree principle.

4. Example Analysis

A nuclear power plant has two million-kilowatt Pressurized Water Reactor (PWR) nuclear power unit. The installed capacity of unit one is 984,000KW, and the unit two also is 984,000KW. This power plant has developed an indicator management system, and established a WANO Benchmarking Comprehensive Query Platform, through analyzing the operational safety performance indicator to improve its safety performance. The article above will evaluate the SPIs of this nuclear power plant.

In this example, the indicator set is $U_{A1-B} = \{u_1, u_2, u_3\}$. Suppose the importance level N=5, and the comment set is $V = \{v_1, v_2, v_3, v_4, v_5\}$ (v_1: Especially Important, v_2: Important, v_3: Relatively Important, v_4: Less Important, v_5: Not Important). If the number of experts is 9, then the importance hierarchy evaluation statistic table is as Table 3:

Table 3. Importance Hierarchy Evaluation of A_1-B Indicators

| A_1-B | Importance Level | | | | | ζj | Weight A | Confidence C |
	1 [0.8,1]	2 [0.6,0.8]	3 [0.4,0.6]	4 [0.2,0.4]	5 [0,0.2]			
u_1	4	4	1	0	0	0.7667	0.3366	0.4444
u_2	4	3	2	0	0	0.7444	0.3268	0.3333
u_3	5	2	2	0	0	0.7667	0.3366	0.2222

According to the formula (1), z_j can be obtained, and the weight vector A and the confidence vector C can be determined by normalization processing. The results are shown in Table 3.

Operational safety performance comment set $V = \{v_1, v_2, v_3, v_4\}$ (v_1: Excellent, v_2: Good, v_3: Fair, v_4: Poor) is known, then the performance hierarchy evaluation statistics are shown in Table 4.

Table 4. Performance Hierarchy Evaluation of A_1-B Indicators

| A_1-B | Evaluation Level | | | |
	Excellent	Good	Fair	Poor
u_1	5	2	2	0
u_2	6	1	2	0
u_3	6	3	0	0

Evaluation matrix can be obtained by normalization processing：

$$R_{A1-B} = \begin{bmatrix} 0.556 & 0.222 & 0.222 & 0 \\ 0.667 & 0.111 & 0.222 & 0 \\ 0.667 & 0.333 & 0 & 0 \end{bmatrix}$$

Preliminary matrix $\overline{B}_{A1-B}$ can be obtained using the formula $\overline{B} = AR$:

$$\overline{B}_{A1-B} = (0.6296, 0.2231, 0.1473, 0) 。$$

Confidence synthetic vector b_{A1-B} can be obtained by using the formula (2) and (3):

$$b_{A1-B} = (0.3993, 0.2391, 0.2092, 0.1524)$$

Final comprehensive evaluation result B_{A1-B} can be determined by multiplying preliminary result $\overline{B}_{A1-B}$ by confidence synthetic vector b_{A1-B} :

$$B_{A1-B} = (0.2514, 0.0534, 0.0308, 0)$$

The weight, confidence level and synthetic confidence of other indicators are showed in Table 5:

Table 5. Relative Calculation of O-A-B Indicators

O-A Index	Weight	Confidence	A-B Index	Weight	Confidence	Synthetic Confidence and Preliminary Vector				
A₁	0.2006	0.5556	B₁	0.3366	0.4444	β	0.3993	0.2391	0.2092	0.1524
			B₂	0.3268	0.3333	B̄	0.6296	0.2231	0.1473	0.0000
			B₃	0.3366	0.2222					
A₂	0.2119	0.6667	B₄	0.3333	0.3333	β	0.3942	0.2632	0.1750	0.1676
			B₅	0.3239	0.4444	B̄	0.6680	0.2960	0.0360	0.0000
			B₆	0.3427	0.5556					
A₃	0.1977	0.1111	B₇	0.3581	0.7778	β	0.3751	0.2473	0.2003	0.1773
			B₈	0.2930	0.2222	B̄	0.6033	0.2960	0.1100	0.0000
			B₉	0.3488	0.6667					
A₄	0.2006	0.3333	B₁₀	0.3589	0.6667	β	0.3916	0.2496	0.1893	0.1695
			B₁₁	0.3110	0.2222	B̄	0.6325	0.2932	0.0744	0.0000
			B₁₂	0.3301	0.5556					
A₅	0.1893	0.3333	B₁₃	0.3237	0.3333	β	0.4031	0.2549	0.1824	0.1597
			B₁₄	0.3140	0.2222	B̄	0.6321	0.2928	0.0751	0.0000
			B₁₅	0.3623	0.6667					

Multiplying preliminary result $\overline{B}$ by confidence β in the Table 5 can get the evaluation result matrix of indicator O-A after normalization processing:

$$R_{O-A} = \begin{bmatrix} 0.7492 & 0.1590 & 0.0918 & 0 \\ 0.7577 & 0.2241 & 0.0181 & 0 \\ 0.7038 & 0.2277 & 0.0685 & 0 \\ 0.7395 & 0.2185 & 0.0420 & 0 \\ 0.7426 & 0.2175 & 0.0399 & 0 \end{bmatrix}$$

Then the preliminary evaluation result $\overline{B}_{O-A}$ can be determined by synthesizing weight A_{O-A} and evaluation matrix R_{O-A} :

$$\overline{B}_{O-A} = \left(0.7389, 0.2094, 0.0518, 0\right)$$

If the model is the basic fuzzy evaluation model, the vector $\overline{B}_{O-A}$ will be the final result. According to the *Maximum Membership Degree* principle, the value 0.7389 is in the maximum assessment level, and then the nuclear power project evaluation result is superior. However, the model used here is not the basic model, but the advanced model introducing confidence level. So, the confidence synthetic vectors should be obtained using the formula (2) and (3) as follows:

$$b_{O-A} = \left(0.3268, 0.2412, 0.2149, 0.2126\right)$$

The confidence vector b_{O-A} shows that the confidence level of excellent is 0.3268, so the evaluation result should be obtained by synthesizing b with preliminary result $\overline{B}$, not using $\overline{B}$ directly.

$$B_{O-A} = \left(0.2415, 0.0505, 0.0114, 0\right)$$

In accordance with *Maximum Membership Degree* principle, it can be seen that the maximum value 0.2415 is in an excellent level. Then, the operational safety performance evaluation result of the nuclear power plant is superior.

5. Conclusion

Through the establishment and calculation of evaluation model, the following conclusions can be drawn:

(1) The index weights of the indicator A_1, A_2, A_3, A_4 and A_5 are average, ranging from the value 0.18 to 0.22, which means that the indicators has an average influence on operational safety performance. The weight of *Combustion Reliability* is relatively larger than other four indicators, so its importance compared to other four indicators is more outstanding.

(2) From the evaluation matrix R_{O-A}, it can be seen that the maximum value of the result vector of Combustion Reliability indicator is 0.7492. According to the *Maximum Membership Degree* principle, the evaluation of *Combustion Reliability* is excellent. Similarly, it can be observed that the other four indicators' evaluation results are all excellent.

(3) From the preliminary evaluation vector $\overline{B}$, it can be directly observed that the preliminary result is excellent. However, from the confidence analysis it can be seen the confidence level of excellent is 0.3268, the confidence level of good is 0.2412, the confidence level of Fair is 0.2194 and the confidence level of Poor is 0.2126. After confidence synthesizing, the final result of operational safety performance evaluation is superior.

The evaluation result in the article can help nuclear operators and regulatory authorities know clearly about the current operational situation of our nuclear power plant, so that to promote the improvement in both nuclear power enterprise management mode and technological level, to further enhance the operational safety of nuclear power plant.

References

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