Research on the Capability Evaluation of Nuclear Emergency Equipment System Based on Multi-level Fuzzy Comprehensive Evaluation Model

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Abstract. The capability evaluation of equipment system is a key work for promoting the capability improvement of equipment system. Scientific capability evaluation of equipment system plays an important role in improving ability of equipment to complete tasks. Firstly, the capability evaluation index system of nuclear emergency equipment system is constructed. Secondly, a multi-level fuzzy comprehensive evaluation model for the capability of nuclear emergency equipment system is established. Finally, the example is evaluated according to the multi-level fuzzy comprehensive evaluation model. The paper provides the method for evaluating the capability of nuclear emergency equipment system scientifically and the direction for its capacity construction.

Keywords: multi-level fuzzy comprehensive evaluation model, nuclear emergency equipment system, capability evaluation

1 Introduction

Nuclear emergency is an emergency action and activity taken to control and mitigate the consequences of nuclear accidents. Equipment system is a higher level system with integrated structure for adapting to the characteristics and laws of the integration task, which is made of equipment that is each other relative in function. The success or failure of nuclear emergency is often related to the capability of nuclear emergency equipment system. Strengthening the capacity construction of nuclear emergency equipment system is crucial to nuclear emergency preparedness. In order to get the direction for its capacity construction, it is necessary to study its capability evaluation.

Now, there is relatively less research on its capability evaluation, and there is also a lack of its complete capability evaluation index system. In this paper, the capability evaluation index system is constructed, the weight is determined by Analytic Hierarchy Process, and a multi-level fuzzy comprehensive evaluation model for its capability is established. This paper offers important reference for its capability evaluation, and the direction for its capacity construction.

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2 Construction of the Capability Evaluation Index System of Nuclear Emergency Equipment System

2.1 Evaluation Index Analysis

Following the establishment principles of the index system: comprehensiveness, scientific, operability, practicability [1], this paper analyzes the factors influencing the capability of the nuclear emergency equipment system. The capability evaluation indexes are divided into five aspects: nuclear emergency command and support, radiation detection, pollution containment, decontamination and recovery, and personnel protection. So, in the capability evaluation indexes, the first-level indexes include nuclear emergency command and support capability, nuclear emergency radiation detection capability, nuclear emergency pollution containment capacity, nuclear emergency decontamination and recovery capacity, nuclear emergency personnel protection capability. To the first-level indexes, nuclear emergency command and support capability is divided into two aspects: nuclear emergency command capability, nuclear emergency support capability. Nuclear emergency radiation detection capability is divided into two aspects: nuclear emergency monitoring capacity [2], nuclear emergency data transmission capability. Nuclear emergency pollution containment capacity is divided into two aspects: nuclear emergency suppression capability [3], operation capability of unmanned machinery for nuclear emergency. Nuclear emergency decontamination and recovery capacity is divided into two aspects: nuclear emergency decontamination capability, nuclear emergency recovery capability. Nuclear emergency personnel protection capability includes single-person emergency action protection capability, personnel breathing support ability, and ability to monitor the vital signs and movement location of nuclear emergency personnel.

2.2 Construction of the Capability Evaluation Index System´

The above is the analysis of the capability indexes of the nuclear emergency equipment system. The capability indexes include 5 first-level indexes, and 11 second-level indexes. The specific capability indexes are shown in Table 1.

Table 1. The capability indexes of nuclear emergency equipment system

	First-level indexes	Second-level indexes
The capability of nuclear emergency equipment system	Nuclear emergency command and support capability(A_1)	Nuclear emergency command capability(A_{11})
		Nuclear emergency support capability(A_{12})
	Nuclear emergency radiation detection capability(A_2)	Nuclear emergency monitoring capacity(A_{21})
		Nuclear emergency data transmission capability(A_{22})

	Nuclear emergency pollution containment capacity(A_3)	Nuclear emergency suppression capability(A_{31})
		Operation capability of unmanned machinery for nuclear emergency(A_{32})
	Nuclear emergency decontamination and recovery capacity(A_4)	Nuclear emergency decontamination capability(A_{41})
		Nuclear emergency recovery capability(A_{42})
	Nuclear emergency personnel protection capability(A_5)	Single-person emergency action protection capability(A_{51})
		Personnel breathing support ability(A_{52})
		Ability to monitor the vital signs and movement location of nuclear emergency personnel(A_{53})

3 Construction of Multi-level Fuzzy Comprehensive Evaluation Model for the Capability of Nuclear Emergency Equipment System

Fuzzy comprehensive evaluation can be divided into one-level fuzzy and multi-level fuzzy evaluation[4]. According to the capability index system, the capability evaluation of nuclear emergency equipment system is a multi-level fuzzy evaluation.

3.1 Weight Calculation of Evaluation Index System

The determination of evaluation index weight has a crucial impact on the scientificity of evaluation results. Analytic Hierarchy Process is adopted to determine the weights of capability indexes of nuclear emergency equipment system[5].

AHP is generally divided into four steps to determine the weights, as follows:

Step 1: Build a hierarchical model

Step 2: Establish the judgment matrix and calculate the weights according to the importance of the indicators

Step 3: Perform hierarchical single sorting, and check consistency

Step 4: Perform hierarchical total sorting

3.2 Construction of Multi-level Fuzzy Comprehensive Evaluation Model

3.2.1 Establishment of Factor set.

If the number of the first-level indicators is n, the factor set U is:

$$U=\{U_1,U_2,U_3,\cdots,U_i,\cdots,U_n\},(i=1,2,3,\cdots,n) \tag{1}$$

If the number of the second-level indicators corresponding to the ith first-level indicator is m, the factor set U_i is:

$$U_i = \left\{U_1^i, U_2^i, U_3^i, \cdots, U_j^i, \cdots, U_m^i\right\}, (j = 1, 2, 3, \cdots, m) \tag{2}$$

3.2.2 Establishment of Weights.

The weights of each factor are determined according to the importance of each factor in its own level, and the constructed weights are as follows:

First-level index weight:

$$W = \begin{pmatrix} W_1 & W_2 & W_3 & \cdots & W_i & \cdots & W_n \end{pmatrix}, (i = 1, 2, 3, \cdots, n) \tag{3}$$

Second-level index weight corresponding to the ith first-level indicator:

$$W_i = \begin{pmatrix} W_1^i & W_2^i & W_3^i & \cdots & W_j^i & \cdots & W_m^i \end{pmatrix}, (j = 1, 2, 3, \cdots, m) \tag{4}$$

3.2.3 Determination of the Set of Comments.

The set of comments V contains all evaluation results, and the number of levels is p.

$$V = \left\{V_1, V_2, V_3, \cdots, V_p\right\}, (p = 1, 2, 3, \cdots) \tag{5}$$

3.2.4 Determination of Membership Matrix.

Single factor $U_i(i=1,2,\ldots)$ in factor set U is conducted for a single factor evaluation. After determining the membership r_{ij} from factor U_i, $\boldsymbol{r}_i = \left(r_{i1}, r_{i2}, \cdots r_{ip}\right), (i = 1, 2, 3, \cdots, n)$ of factor U_i is obtained. The total evaluation matrix is obtained by taking n single factor evaluation sets as rows[6].

$$R = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1p} \\ r_{21} & \cdots & \cdots & r_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{np} \end{pmatrix} \tag{6}$$

r_{ij} represents the membership degree of the factor.

3.2.5 First-level Fuzzy Comprehensive Evaluation.

The evaluation of the second-level indexes to the first-level indexes is regarded as first-level fuzzy comprehensive evaluation. Since the factors of the first-level indexes determine and dominate the factors of the second-level indexes, the multi-factor evaluation results of the first-level indexes will be influenced by multi-factors evaluation results of the second-level indexes [7]. Therefore, R_i is the single factor evaluation matrix of the second-level indexes.

$$R_i = \begin{pmatrix} r_{11}^i & r_{12}^i & \cdots & r_{1p}^i \\ r_{21}^i & r_{22}^i & \cdots & r_{2p}^i \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1}^i & r_{m2}^i & \cdots & r_{mp}^i \end{pmatrix} \tag{7}$$

The first-level fuzzy comprehensive evaluation vector B_i is:

$$B_i = W_i * R_i = \begin{pmatrix} W_1^i & W_2^i & \cdots & W_m^i \end{pmatrix} * \begin{pmatrix} r_{11}^i & r_{12}^i & \cdots & r_{1p}^i \\ r_{21}^i & r_{22}^i & \cdots & r_{2p}^i \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1}^i & r_{m2}^i & \cdots & r_{mp}^i \end{pmatrix} = \begin{pmatrix} b_{i1} & b_{i2} & \cdots & b_{ip} \end{pmatrix} \tag{8}$$

“*” is matrix dot multiplication in that.[8]

3.2.6 Fuzzy Comprehensive Evaluation.

The evaluation of the target level to the first-level indexes is regarded as fuzzy comprehensive evaluation. It is necessary to calculate the comprehensive membership vector based on the results of the first-level fuzzy comprehensive evaluation. Let Q be the comprehensive membership vector, and Q is:

$$Q = W * \begin{pmatrix} B_1 \\ B_2 \\ \vdots \\ B_n \end{pmatrix} \tag{9}$$

P is the rating vector, and the evaluation value E is obtained

$$E = P * Q^T \tag{10}$$

4 Example Analysis

Taking the capability of a unit's nuclear emergency equipment system as an example, this paper evaluates the capability of the unit's nuclear emergency equipment system by multi-level fuzzy comprehensive evaluation model.

4.1 Weight Calculation of Evaluation Index System

The weights of each layer are calculated according to the steps of AHP.

By sending a questionnaire to experts to determine the relative importance of the two indicators, the questionnaire data is collected and analyzed, and the weights of the evaluation indicators are calculated.

Now the weights of the first-level indexes are calculated. Expert evaluation form is shown in Table 2:

Table 2. Expert evaluation form

	A_1	A_2	A_3	A_4	A_5
A_1	1	3	2	2	7
A_2	1/3	1	1/2	1/2	1/3
A_3	1/2	2	1	1	4
A_4	1/2	2	1	1	2
A_5	1/7	3	1/4	1/2	1

Using the above table, we obtain the judgment matrix:

$$A=\begin{pmatrix} 1 & 3 & 2 & 2 & 7 \\ 1/3 & 1 & 1/2 & 1/2 & 1/3 \\ 1/2 & 2 & 1 & 1 & 4 \\ 1/2 & 2 & 1 & 1 & 2 \\ 1/7 & 3 & 1/4 & 1/2 & 1 \end{pmatrix}$$

Multiplying the elements of each row in the matrix, we obtain: $M_i=\prod_{i=1}^{5} a_i$

Finding the 5th root of M_i, we obtain: $\overline{W_i}=\sqrt[5]{\prod_{i=1}^{5} a_i}$

Normalizing the vector $\overline{W_i}$, we obtain:

$$W=\frac{\overline{W_i}}{\sum_{i=1}^{n}\overline{W_i}}=\begin{pmatrix} 0.407 \\ 0.085 \\ 0.221 \\ 0.183 \\ 0.104 \end{pmatrix}^T$$

The matrix can be considered consistent. The procedure for calculating the weights of the second-level indexes is the same.

The weight calculation results of the capability indexes of the unit's nuclear emergency equipment system are shown in Table 3.

Table 3. Weight results of the capability indexes

	First-level indexes	Weight	Second-level indexes	Weight
The capability of nu-	Nuclear emergency command and support capability(A_1)	0.407	Nuclear emergency command capability(A_{11})	0.75
			Nuclear emergency support capability(A_{12})	0.25
		0.085	Nuclear emergency monitoring capacity(A_{21})	0.5

clear emergency equipment system	Nuclear emergency radiation detection capability(A_2)		Nuclear emergency data transmission capability(A_{22})	0.5
	Nuclear emergency pollution containment capacity(A_3)	0.221	Nuclear emergency suppression capability(A_{31})	0.666
			Operation capability of unmanned machinery for nuclear emergency(A_{32})	0.333
	Nuclear emergency decontamination and recovery capacity(A_4)	0.183	Nuclear emergency decontamination capability(A_{41})	0.8
			Nuclear emergency recovery capability(A_{42})	0.2
	Nuclear emergency personnel protection capability(A_5)	0.104	Single-person emergency action protection capability(A_{51})	0.539
			Personnel breathing support ability(A_{52})	0.297
			Ability to monitor the vital signs and movement location of nuclear emergency personnel(A_{53})	0.163

4.2 Comprehensive Evaluation of the Capability of the Unit's Nuclear Emergency Equipment

4.2.1 Establishing Factor Set.

$U=\{A_1, A_2, A_3, A_4, A_5\}$ $U_1=\{A_{11}, A_{12}\}$ $U_2=\{A_{21}, A_{22}\}$

$U_3=\{A_{31}, A_{32}\}$ $U_4=\{A_{41}, A_{42}\}$ $U_5=\{A_{51}, A_{52}, A_{53}\}$

4.2.2 Determining the Weights.

$$W=\begin{pmatrix} w_1 & w_2 & w_3 & w_4 & w_5 \end{pmatrix}=\begin{pmatrix} 0.407 \\ 0.085 \\ 0.221 \\ 0.183 \\ 0.104 \end{pmatrix}^T \qquad W_1=\begin{pmatrix} 0.75 & 0.25 \end{pmatrix}$$

$$W_2=\begin{pmatrix} 0.5 & 0.5 \end{pmatrix} \qquad W_3=\begin{pmatrix} 0.666 & 0.333 \end{pmatrix}$$

$$W_4=\begin{pmatrix} 0.8 & 0.2 \end{pmatrix} \qquad W_5=\begin{pmatrix} 0.539 & 0.297 & 0.163 \end{pmatrix}$$

4.2.3 Determining the set of Comments.

The set of comments is represented by five levels of "very poor, poor, average, good, very good ", and five fuzzy levels respectively, and their values are represented, as shown in Table 4.

Table 4. Evaluation criteria

Rank	value	Rank	value	Rank	value	Rank	value	Rank	value
very poor	50	poor	60	average	70	good	80	very good	90

meanwhile $P = (90, 80, 70, 60, 50)$

4.2.4 Determination of Membership Matrix.

Membership degree is calculated as follows:

A questionnaire is sent to 10 experts to evaluate the secondary indicators. After the questionnaire is collected, the evaluation results are shown in Table 5:

Table 5. Statistical table of evaluation results

Specific evaluation item			Evaluation level				
	First-level indexes	Second-level indexes	very good	good	average	poor	very poor
The capability of nuclear emergency equipment system	Nuclear emergency command and support capability(A_1)	Nuclear emergency command capability(A_{11})	7	2	1		
		Nuclear emergency support capability(A_{12})	6	3	1		
	Nuclear emergency radiation detection capability(A_2)	Nuclear emergency monitoring capacity(A_{21})	2	5	3		
		Nuclear emergency data transmission capability(A_{22})	5	4	1		
	Nuclear emergency pollution containment capacity(A_3)	Nuclear emergency suppression capability(A_{31})	5	1	4		
		Operation capability of unmanned machinery for nuclear emergency(A_{32})	6	3		1	
	Nuclear emergency decontamination and recovery capacity(A_4)	Nuclear emergency decontamination capability(A_{41})		4	5	1	
		Nuclear emergency recovery capability(A_{42})	1	4	4	1	
	Nuclear emergency personnel protection capability(A_5)	Single-person emergency action protection capability(A_{51})	5	4	1		
		Personnel breathing support ability(A_{52})	4	2	3	1	
		Ability to monitor the vital signs and movement location of nuclear emergency personnel(A_{53})	5	3	2		

The membership matrices constructed are:

$$R_1 = \begin{pmatrix} 0.7 & 0.2 & 0.1 & 0 & 0 \\ 0.6 & 0.3 & 0.1 & 0 & 0 \end{pmatrix} \qquad R_2 = \begin{pmatrix} 0.2 & 0.5 & 0.3 & 0 & 0 \\ 0.5 & 0.4 & 0.1 & 0 & 0 \end{pmatrix}$$

$$R_3 = \begin{pmatrix} 0.5 & 0.1 & 0.4 & 0 & 0 \\ 0.6 & 0.3 & 0 & 0.1 & 0 \end{pmatrix} \qquad R_4 = \begin{pmatrix} 0 & 0.4 & 0.5 & 0.1 & 0 \\ 0.1 & 0.4 & 0.4 & 0.1 & 0 \end{pmatrix}$$

$$R_5 = \begin{pmatrix} 0.5 & 0.4 & 0.1 & 0 & 0 \\ 0.4 & 0.2 & 0.3 & 0.1 & 0 \\ 0.5 & 0.3 & 0.2 & 0 & 0 \end{pmatrix}$$

4.2.5 First-level Fuzzy Comprehensive Evaluation.

The evaluation vector B_1 of nuclear emergency command and support capability is:

$$W_1 = \begin{pmatrix} 0.750 & 0.250 \end{pmatrix} \qquad R_1 = \begin{pmatrix} 0.7 & 0.2 & 0.1 & 0 & 0 \\ 0.6 & 0.3 & 0.1 & 0 & 0 \end{pmatrix}$$

$$B_1 = W_1 * R_1 = \begin{pmatrix} 0.675 & 0.225 & 0.100 & 0 & 0 \end{pmatrix}$$

Similarly, the evaluation vector B_2 of nuclear emergency radiation detection capability is:

$$B_2 = W_2 * R_2 = \begin{pmatrix} 0.35 & 0.45 & 0.2 & 0 & 0 \end{pmatrix}$$

The evaluation vector B_3 of nuclear emergency pollution containment capability is:

$$B_3 = W_3 * R_3 = \begin{pmatrix} 0.533 & 0.167 & 0.266 & 0.033 & 0 \end{pmatrix}$$

The evaluation vector B_4 of nuclear emergency decontamination and recovery capability is:

$$B_4 = W_4 * R_4 = \begin{pmatrix} 0.02 & 0.4 & 0.48 & 0.1 & 0 \end{pmatrix}$$

The evaluation vector B_5 of nuclear emergency personnel protection capability is:

$$B_5 = W_5 * R_5 = \begin{pmatrix} 0.470 & 0.324 & 0.176 & 0.030 & 0 \end{pmatrix}$$

4.2.6 Fuzzy Comprehensive Evaluation.

$$W = \begin{pmatrix} 0.407 & 0.085 & 0.221 & 0.183 & 0.104 \end{pmatrix}$$

$$Q = \begin{pmatrix} 0.675 & 0.225 & 0.1 & 0 & 0 \\ 0.35 & 0.45 & 0.2 & 0 & 0 \\ 0.533 & 0.167 & 0.266 & 0.033 & 0 \\ 0.02 & 0.4 & 0.48 & 0.1 & 0 \\ 0.470 & 0.324 & 0.176 & 0.030 & 0 \end{pmatrix}$$

$$S = W * Q = \begin{pmatrix} 0.475 & 0.273 & 0.223 & 0.029 & 0 \end{pmatrix}$$

E is used to represent the capability score of a unit's nuclear emergency equipment system.

The comprehensive score of the capability of the unit's nuclear emergency equipment:

$$E = \begin{pmatrix} 90 & 80 & 70 & 60 & 50 \end{pmatrix} * S^T = 81.94$$

The score of nuclear emergency command and support capability:

$$E_1 = \begin{pmatrix} 90 & 80 & 70 & 60 & 50 \end{pmatrix} * B_1^T = 85.75$$

The score of nuclear emergency radiation detection capability:

$$E_2 = \begin{pmatrix} 90 & 80 & 70 & 60 & 50 \end{pmatrix} * B_2^T = 81.5$$

The score of nuclear emergency pollution containment capability:

$$E_3 = \begin{pmatrix} 90 & 80 & 70 & 60 & 50 \end{pmatrix} * B_3^T = 81.93$$

The score of nuclear emergency decontamination and recovery capacity:

$$E_4 = \begin{pmatrix} 90 & 80 & 70 & 60 & 50 \end{pmatrix} * B_4^T = 73.4$$

The score of nuclear emergency personnel protection capability:

$$E_5 = \begin{pmatrix} 90 & 80 & 70 & 60 & 50 \end{pmatrix} * B_5^T = 82.34$$

The final score of the capability of the unit's nuclear emergency equipment system is 81.94, and the capability can be judged as "good".But the score of nuclear emergency decontamination and recovery capacity is 73.4,it is “average level”.To the unit's nuclear emergency equipment system construction , this is what in the subsequent construction need to be strengthened. To the indexes with high evaluation value, we should continue to strengthen the equipment construction to maintain its original advantages; To the indexes with low evaluation value, it is necessary to focus on strengthening them.

5 Conclusion

This paper establishs the capability evaluation index system of nuclear emergency equipment system, a multi-level fuzzy comprehensive evaluation model for the capability of nuclear emergency equipment system. The paper provides the scientific method for its capability evaluation, and the direction for its capacity construction. The research can solve the problem about its capability evaluation very well, and it lays the foundation for the completion of the nuclear emergency tasks.

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