Assessment of Emergency Capability for Chemical Enterprise Based on Analytic Hierarchy Process and Extension Theory

Zhenhua Xie[1(✉)], Zhenxiong Xing[2], and Mingzhi Xu[2]

[1] School of Safety Engineering, China University of Labor Relations, Beijing 100048, China
xie0015@sina.com

[2] Guizhou Academy of Labor Protection Science and Technology, Zunyi Guizhou 563000, China

Abstract. Timely and accurate assessment of the emergency capability of chemical enterprises can provide scientific guidance for improving the emergency capability of chemical enterprises. According to relevant laws and regulations, combined with literature analysis and field investigation, the index system of emergency capacity assessment of chemical enterprises was established. The system consists of four first-level indexes, including emergency prevention capability, emergency preparation capability, emergency response capability, emergency rescue capability and 20 s-level indexes. Based on analytic hierarchy process, the weight of assessment index of chemical enterprise emergency capability was determined. This method can fully reflect the objectivity and comprehensiveness of data. The emergency capability assessment method based on extension theory is discussed and applied in a chemical enterprise, and accurate and objective assessment results are obtained. The method is scientific and practical, and can effectively reduce the accident risk of chemical enterprises.

Keywords: analytic hierarchy process (AHP) · extension theory · chemical enterprises · emergency capability · assessment method

1 Introduction

China has the largest chemical industry in the world, and chemical industry is developing rapidly. The production process of chemical enterprises is complicated and involves many inflammable, explosive toxic and hazardous chemicals. Once the safety risk control fails, accidents such as fire, explosion and poisoning are easy to occur, and will result in heavy casualties and property losses. For example, on March 21, 2019, a chemical storage tank explosion occurred at Tianjiayi Chemical Co., Ltd. in Yancheng City, Jiangsu Province, China, resulting in 78 deaths and 76 serious injuries and a direct economic loss of 1.986 billion yuan. On February 26, 2021, four people were killed and four others injured in a methyl sulphide explosion at a chemical company in Xianlong, Hubei

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Province, China, during the resumption of production. Therefore, chemical enterprises must take effective measures to prevent accidents according to relevant safety laws and regulations, enhance the emergency capability for accident, take measures to deal with accidents quickly and effectively, and reduce accident losses. Timely and accurately carrying out the emergency capacity assessment of chemical enterprises can find the shortage of emergency management in time, meet the needs of emergency decision-making, and improve the emergency capacity of enterprises.

Scholars have carried out some research on the emergency capacity assessment of city, traffic, industrial and mining enterprises. For example, Zhang Jianjun established the theoretical system of highway traffic emergency capability assessment [1]. Li Zhenyu et al. carried out an assessment of power grid emergency capability based on the theory of binary connection-projection grey target decision [2]. Wang Di et al. proposed a dynamic comprehensive evaluation method of power grid emergency capability based on fuzzy - two-stage super efficiency SBM model [3]. Yang Zhenhong et al. assess the emergency management capability of chemical parks based on the extension theory [4]. However, there are few researches on the assessment of emergency capability of chemical enterprises.

First, it is necessary to establish an assessment index system to assess emergency capability. Yang Li and Yang Sanjun et al. established the assessment index system of emergency rescue ability of coal mine and mine rescue team through literature analysis and questionnaire [5, 6]. Chen Dajun et al. constructed an assessment index system of railway emergency rescue capability under major epidemic situations from three aspects: railway emergency preparedness, emergency response and emergency recovery [7]. The methods to determine the weight of assessment index mainly include Delphi method, analytic hierarchy process (AHP), improved AHP hierarchical entropy analysis, etc. [8–10]. There are relatively more researches on assessment methods, such as fuzzy comprehensive evaluation method [11], neural network method [12], extension theory method [13] and so on. Guo Yuntao et al. proposed an emergency capacity assessment model of chemical parks based on cloud barycenter assessment method, which solved the conversion problem between qualitative concepts and quantitative values [14]. Han Xinxing used cross impact analysis method and interpretive structure model method to construct and deduce enterprise emergency scenarios, and carried out enterprise emergency capability assessment [15]. The above research results provide reference for the construction of the assessment index system of chemical enterprises' emergency capability and the selection of assessment methods. However, it is necessary to carry out the assessment of emergency capability in combination with the characteristics of chemical enterprises' emergency capability.

According to the characteristics of safety production of chemical enterprises and the requirements of emergency capacity construction, this paper establishes a comprehensive assessment index system of emergency capacity of chemical enterprises, determines the weight of assessment index of emergency capacity of chemical enterprises based on analytic hierarchy process, adopts the extension theory to carry out emergency capacity assessment of chemical enterprises, and will provide scientific guidance for the improvement of emergency capacity of chemical enterprises.

2 Establishment and Weight Determination of Assessment Index System of Chemical Enterprise Emergency Capacity

2.1 Establishment of Assessment Index System of Chemical Enterprise Emergency Capacity

According to Work Safety Law of the People's Republic of China, Emergency Response Law of the People's Republic of China and other laws and regulations, and combining with the requirements of accident emergency, emergency work can be divided into three stages: before the event, during the event and after the event. Emergency capacity should include emergency prevention capacity, emergency preparedness capacity, emergency response capacity, emergency recovery capacity, and each aspect can be divided into different elements. For example, according to the Guidelines on Emergency Preparedness for Production Safety Accidents in Hazardous Chemical Enterprises, the contents of emergency preparedness consist of 14 elements including ideology and idea, organization and responsibilities, laws and regulations, risk assessment, plan management, monitoring and early warning, education training and drill, on duty and guard, information management, equipment and facilities, rescue team construction, emergency disposal and rescue, emergency preparedness recovery, fund guarantee, each of which is divided into several projects. By referring to the research results of related literature mentioned above and the author's field investigation of several chemical enterprises, the assessment indexes of emergency capability of chemical enterprises are initially selected, and then the [5]. On the premise of not losing the system function, applying Interpretation Structure Model (ISM) method, the simplest hierarchical topology diagram is presented, and the model system of emergency capability assessment of chemical enterprises is condensed. The system consists of 4 first-level indexes and 20 s-level indexes, as shown in Table 1.

2.2 Determination of Assessment Index Weight

As there are many factors affecting the emergency capability of chemical enterprise, the fuzzy uncertainty of the assessment indexes is relatively high, and the amount of data involved is large and inconsistent, so it is difficult to achieve objective and accurate quantitative. On the basis of comparative analysis, the analytic hierarchy process is selected to determine the weight of assessment indexes, which can reflect the importance of assessment indexes objectively and comprehensively.

The analytic hierarchy process constructs the judgment matrix by comparing the importance of the assessment indexes at the same level in pairs, and then obtains the weight of the indexes through calculation, and finally determines the final weight of the indexes through consistency test. The construction of the judgment matrix is generally based on the scale method of 1 ~ 9, and the elements of the matrix are obtained by pairwise comparison. The judgment scale and its meaning are shown in Table 2. The matrix element $r_{ji} = 1/r_{ij}$.

Taking emergency prevention capability as an example, the constructed judgment matrix is shown in Table 3.

Table 1. Index system of emergency capability assessment for chemical enterprise

First-level index	Second-level index	Explain of the index
Emergency prevention capacity *A*1	Emergency idea *B*1	Establish a sense of the red line for safety development, ensure that enterprises are responsible for production safety, establish a bottom-line thinking for risk prevention and control, adhere to life first and science emergency, etc.
	Emergency organization and responsibility *B*2	Establish sound emergency rescue organizations, clarify the responsibilities and tasks of each organization, etc.
	Emergency laws and regulations *B*3	Identify and strictly implement laws and regulations related to safety production in chemical enterprises, etc.
	Emergency rules and system *B*4	Formulate perfect emergency management system and operation rules, and effectively implement and manage, etc.
	Risk assessment *B*5	Risk identification, risk analysis, risk assessment, scenario construction, etc.
	Hidden danger investigation and treatment *B*6	Hidden danger investigation, hidden danger statistical analysis, risk prevention and control, hidden danger treatment, etc.
Emergency preparedness capacity *A*2	Monitoring and early warning *B*7	Hazard source monitoring, early warning analysis, forecast and early warning, early warning measures, etc.
	Emergency plans management *B*8	Emergency plans draw, emergency plans management, ability enhancement, etc.

(*continued*)

Table 1. (*continued*)

First-level index	Second-level index	Explain of the index
	Education, training and drill *B*9	Emergency publicity, emergency education and training, emergency drill, drill assessment, etc.
	Emergency team construction *B*10	Setting of full-time and part-time emergency teams, training and exercise, team management, rescue joint action, etc.
	Emergency facilities and equipment *B*11	Setting of emergency facilities, provision of emergency supplies and equipment, maintenance and management of emergency facilities and equipment, etc.
	Emergency information management *B*12	Emergency information collection and analysis, establishment and operation of emergency information system, information assurance, etc.
	Emergency fund guarantee *B*13	Source security and budget of emergency funds, use and commitment of rescue funds, etc.
Emergency response capability *A*3	Emergency on duty and guard *B*14	Emergency on duty and guard, accident information received, External notification, etc.
	Emergency command *B*15	Establishment of emergency command system, emergency decision, unified allocation of resources, department communication, response grading, response program, etc.

(*continued*)

Table 1. (*continued*)

First-level index	Second-level index	Explain of the index
	Emergency treatment and rescue *B*16	Personnel evacuating, medical aid, on-site emergency measures, emergency treatment of hazardous chemicals, engineering rescue, union rescue, etc.
Emergency recovery capability *A*4	Aftermath deal with *B*17	Site disposal, accident indemnity, personnel comfort, accident investigation and analysis, etc.
	Emergency rescue assessment *B*18	Procedures and methods for emergency assessment, assessment report, archives management, etc.
	Emergency recovery and reconstruction *B*19	Recovery of production order, emergency recovery planning, implementation of emergency recovery, etc.
	Continuous improvement *B*20	Emergency improvement plan, implementation of emergency improvements, emergency improvement acceptance, etc.

Table 2. Judgment scale and its meaning

Scale (matrix element r_{ij})	Scale meaning
1	Index X_{i} is as important as index X_j
3	Index X_{i} is slightly more important than index X_j
5	Index X_{i} is important than index
7	Index X_{i} is more important than index
9	Index X_{i} is absolutely more important than index
2, 4, 6, 8	Corresponds to the intermediate situation of the above two adjacent indexes

Table 3. Weight calculation of emergency prevention capability

	Emergency idea *B*1	Emergency organization and responsibility *B*2	Emergency laws and regulations *B*3	Emergency rules and system *B*4	Risk assessment *B*4	Hidden danger investigation and treatment *B*5	w_1
Emergency idea *B*1	1	0.2	0.333	0.167	0.143	0.111	0.023
Emergency organization and responsibility *B*2	5	1	3	0.333	0.2	0.143	0.112
Emergency laws and regulations *B*3	3	0.333	1	0.2	0.167	0.143	0.056
Emergency rules and system *B*4	6	3	5	1	0.333	0.2	0.180
Risk assessment *B*5	7	5	6	3	1	0.333	0.258
Hidden danger investigation and treatment *B*6	9	7	7	5	3	1	0.371

Using yaahp software to calculate, the secondary index weight of emergency prevention capability A1 can be obtained as wB1 = 0.023, wB2 = 0.112, wB3 = 0.056, wB4 = 0.180, wB5 = 0.258, wB6 = 0.371. Similarly, the first-level index weight of emergency capability assessment of chemical enterprises is wA1 = 0.286, wA2 = 0.381, wA3 = 0.190, wA4 = 0.143, and the weight of other secondary indexes are wB7 = 0.128, wB8 = 0.205, wB9 = 0.179, wB10 = 0.128, wB11 = 0.154, wB12 = 0.103, wB13 = 0.103, wB14 = 0.316, wB15 = 0.263, wB16 = 0.421, wB17 = 0.136, wB18 = 0.273, wB19 = 0.364, wB20 = 0.227

3 Emergency Capability Assessment Method Based on Extension Theory

The extension theory solves the contradiction problem of fuzzy diversity of assessment objects from qualitative and quantitative perspectives and has been successfully applied in many fields. The parametric matter-element model in extension theory is a dynamic model. By introducing the concept of matter-element $R = (N, C, V)$, the things N to be assessed, feature C of things and the specific value V of features are organically combined, which can better solve the incompatibility problem of indexes in comprehensive assessment. Therefore, this paper builds an extension assessment model for the emergency capability of chemical enterprises based on the extension theory.

3.1 Determination of Classical Domain Matter Element, Node Domain Matter Element, Awaiting Assessed Matter Element

1) classical domain matter element

$$R_j = \left(N_j, C_i, V_{ji}\right) = \begin{bmatrix} N_j & c_1 & v_{j1} \\ & c_2 & v_{j2} \\ & \vdots & \vdots \\ & c_n & v_{jn} \end{bmatrix} = \begin{bmatrix} N_j & c_1 & < a_{j1}, b_{j1} > \\ & c_2 & < a_{j2}, b_{j2} > \\ & \vdots & \vdots \\ & c_n & < a_{jn}, b_{jn} > \end{bmatrix} \tag{1}$$

In formula, N_j represents j levels of emergency capability assessment, $j = (1, 2, \ldots, m)$; C_i represents the i'th assessment index, $i = (1, 2, \ldots, n)$; V_{ji} represents value range of level N_j for C_i, namely classical domain, $V_{ji} = < a_{j1}, b_{j1} >$, a_{j1} is the lower limit of the value, b_{j1} is the upper limit.

2) node domain matter element

$$R_p = (N, C_i, V_{pi}) = \begin{bmatrix} N & c_1 & v_{p1} \\ & c_2 & v_{p2} \\ & \vdots & \vdots \\ & c_n & v_{pn} \end{bmatrix} = \begin{bmatrix} N & c_1 & < a_{p1}, b_{p1} > \\ & c_2 & < a_{p2}, b_{p2} > \\ & \vdots & \vdots \\ & c_n & < a_{pn}, b_{pn} > \end{bmatrix} \tag{2}$$

In formula, N represents the total emergency capacity assessment level; V_{pi} is the range of all values of C_i at level N, namely nodal domain of N, $V_{pi} = < a_{p1}, b_{p1} >$. Obviously, there is $< a_{j1}, b_{j1} > \subset < a_{p1}, b_{p1} >$.

3) awaiting assessed matter element

$$R_x = (N_x, C_i, V_i) = \begin{bmatrix} N_x & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix} \tag{3}$$

In formula, Nx represents the grade of a chemical enterprise to be assessed; Vi is the specific data of Nx about the index Ci, namely the assessment results of each assessment index of a chemical enterprise by experts.

3.2 Determination of Correlation Degree

1) determination of the correlation degree of each assessment index with respect to each assessment level Kj(vi)

$$K_j(v_i) = \begin{cases} \frac{-\rho(v_i, v_{ji})}{|v_{ji}|} & (v_i \in V_{ji}) \\ \frac{\rho(v_i, v_{ji})}{\rho(v_i, v_{pi}) - \rho(v_i, v_{ji})} & (v_i \notin V_{ji}) \end{cases} \tag{4}$$

In formula, $\rho(v_i, v_{ji})$ is the distance between point vi and interval Vji. The calculation formula is

$$|V_{ji}| = b_{ji} - a_{ji} \tag{5}$$

$$\rho(v_i, v_{ji}) = \left| v_i - \frac{a_{ji} + b_{ji}}{2} \right| - \frac{1}{2}(b_{ji} - a_{ji}) \tag{6}$$

$$\rho(v_i, v_{pi}) = \left| v_i - \frac{a_{pi} + b_{pi}}{2} \right| - \frac{1}{2}(b_{pi} - a_{pi}) \tag{7}$$

2) determination of the comprehensive correlation degree of the awaiting assessed matter element with respect to the assessment level

According to the weight of each emergency capacity assessment index w_i ($\sum_{i=1}^{n} w_i = 1$), the single correlation degree $K_j(v_i)$ and weight value are synthesized into comprehensive correlation degree $K_j(N_x)$, namely, the correlation degree of N_x of chemical enterprise to be assessed with regard to warning level *j*.

$$K_j(N_x) = \sum_{i=1}^{n} w_i K_j(v_i) \tag{8}$$

3.3 Determination of the Assessment Level

If $K_j = max_{j \in (1,2 \cdots, m)} k_j(N_x)$, then the emergency capability level of the assessed object N_x is *j*, which is the level corresponding to the maximum value.

If the assessment index of the assessment object is divided into different levels or the weight of the assessment index is too small, the multi-level comprehensive extension assessment model should be adopted. The calculation method of the multilevel comprehensive extension assessment model is like that of the single level. The assessment results of the second level form the assessment matrix K1 of the first level, and then combine the weight W of the assessment index of the first level to get the final assessment result K.

$$\mathrm{K} = \mathrm{W} \cdot \mathrm{K}_1 \tag{9}$$

4 Application of Emergency Capacity Assessment Method

4.1 Application Case Overview

Shandong Binzhou Petrochemical Co., Ltd. is a petrochemical industry as the main business, set petroleum refining and subsequent deep processing as one of the large enterprises. The company's products involve high-efficiency fuel, high-end chemical products, high-performance materials three plates, including automotive gasoline, food additives, cleaning agent, cleaning rubber, etc. The enterprise attaches great importance to product quality and safety production work, adhere to the safety idea that safety is the day, life is more important than Mount Tai, and constantly strengthen safety technical measures and safety management. The enterprise has a company-level and factory-level safety management organization, equipped with full-time and part-time safety production management personnel, has formulated a relatively complete safety production management system and safety operation procedures. The company has passed the OHSAS 18001 international Occupational Health and safety management system certification, won *the Science and Technology Progress enterprise Award* and *five-star site management recognition* and other honorary titles.

4.2 Determination of the Assessment Element of the Enterprise

The assessment grade of the emergency capability of the chemical enterprise was divided into four grades, namely, N_1, N_2, N_3, N_4. The value range of each assessment index in each grade can be divided into [100, 90], [90, 75], [75, 60], [60, 0]. Ten experts from scientific research institutions, universities and chemical enterprises were invited to score the emergency capability of the chemical enterprise according to the assessment index system, and the average score of each assessment index was calculated as the assessment score. Take emergency prevention capacity A_1 as an example.

$$R_1 = (N_1, C_i, V_{1i}) = \begin{bmatrix} N_1 & \text{Emergency idea} & <100,\ 90> \\ & \text{Emergency organization and responsibility} & <100,\ 90> \\ & \text{Emergency laws and regulations} & <100,\ 90> \\ & \text{Emergency rules and system} & <100,\ 90> \\ & \text{Risk assessment} & <100,\ 90> \\ & \text{Hidden danger investigation and treatment} & <100,\ 90> \end{bmatrix}$$

$$R_2 = (N_2, C_i, V_{2i}) = \begin{bmatrix} N_2 & \text{Emergency idea} & <90,\ 75> \\ & \text{Emergency organization and responsibility} & <90,\ 75> \\ & \text{Emergency laws and regulations} & <90,\ 75> \\ & \text{Emergency rules and system} & <90,\ 75> \\ & \text{Risk assessment} & <90,\ 75> \\ & \text{Hidden danger investigation and treatment} & <90,\ 75> \end{bmatrix}$$

R_3, R_4 is similar.

$$R_p = (N, C_i, V_{pi}) = \begin{bmatrix} N & \text{Emergency idea} & <100,\ 0> \\ & \text{Emergency organization and responsibility} & <100,\ 0> \\ & \text{Emergency laws and regulations} & <100,\ 0> \\ & \text{Emergency rules and system} & <100,\ 0> \\ & \text{Risk assessment} & <100,\ 0> \\ & \text{Hidden danger investigation and treatment} & <100,\ 0> \end{bmatrix}$$

$$R_x = (N_x, C_i, V_i) = \begin{bmatrix} N_x & \text{Emergency idea} & 92 \\ & \text{Emergency organization and responsibility} & 82 \\ & \text{Emergency laws and regulations} & 91 \\ & \text{Emergency rules and system} & 85 \\ & \text{Risk assessment} & 80 \\ & \text{Hidden danger investigation and treatment} & 90 \end{bmatrix}$$

4.3 Determination of Assessment Relevance of the Enterprise

According to formulas (4)~(7), the correlation degree of each assessment index to each assessment level is calculated, and the correlation matrix of emergency prevention capacity to each assessment level is

$$K_1(1) = \begin{bmatrix} 0.8 & 0.23 & 0.53 & 0 \\ 0.22 & 0.53 & 0.27 & 0 \\ 0.9 & 0.21 & 0.27 & 0 \\ 0.21 & 0.67 & 0.42 & 0 \\ 0.33 & 0.67 & 0.33 & 0 \\ 1 & 0.2 & 0.5 & 0 \end{bmatrix}$$

Then, according to the weight w1 = (0.023, 0.112, 0.1056, 0.180, 0.256, 0.371) of each secondary index of emergency prevention capacity, the comprehensive correlation degree of emergency prevention capacity can be obtained from Eq. (8): K11 = w1·K1(1) = (0.606, 0.404, 0.409, 0). By the same token, the comprehensive correlation degree K12, K13, K14 of the first-level index emergency preparedness capacity, emergency response capacity, and emergency recovery capacity can be obtained to form the assessment matrix K1:

$$K_1 = \begin{bmatrix} 0.606 & 0.404 & 0.409 & 0 \\ 0.352 & 0.567 & 0.473 & 0 \\ 0.423 & 0.621 & 0.427 & 0 \\ 0.339 & 0.428 & 0.635 & 0.238 \end{bmatrix}$$

According to the weight $w = (0.286, 0.381, 0.190, 0.143)$ of the first-order index, it can be obtained from Eq. (9).

$$K = W \cdot K1 = (0.442, 0.511, 0.469, 0.034)$$

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4.4 Determination and Verification of the Enterprise Emergency Capability Assessment Level

Because maximum value of K is 0.511, therefore the emergency capability assessment level of this chemical enterprise is level 2, which is good. The enterprise has established an emergency management organization, formulated emergency related management systems, equipped with full-time and part-time emergency management personnel, all kinds of emergency rescue facilities and equipment is relatively complete. The enterprise has formulated a systematic and complete emergency plan system, and regularly carries out emergency training and emergency drills. Therefore, the assessment results are consistent with the overall situation of the enterprise's emergency capability and the experts' overall understanding, indicating that the emergency capability assessment method based on extension theory is scientific and practical.

5 Conclusions

(1) According to relevant laws and regulations and comprehensive analysis, a model system of emergency capability assessment of chemical enterprise can be established by using the interpretive structure model method. The system consists of four first-level indexes, including emergency prevention capability, emergency preparedness capability, emergency response capability, emergency rescue capability, and 20 s-level indexes.

(2) The analytic hierarchy process (AHP) can determine the weight of the assessment index of the emergency capability of chemical enterprises, which can fully reflect the objectivity and comprehensiveness of the data.

(3) The application of extension theory in the assessment of chemical enterprises' emergency capacity can effectively solve the fuzzy diversity contradiction of the assessment objects, obtain objective and accurate assessment results, and provide scientific guidance for the improvement of chemical enterprises' emergency capacity.

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