

# Research on safety sustainability of LNG tanks based on multi-attribute decision-making-FCEM coupled modeling

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**Abstract:** Against the backdrop of the “dual carbon goals”, China has been advancing its “coal-to-gas transition” strategy, during which LNG leakage incidents have occurred frequently. Addressing the challenge of assessing the interrelated risks of multiple factors, this study constructs an ANP-CRITIC-FCEM coupled model, establishing a micro-level risk identification system from five dimensions: “environment, equipment, process, personnel, and materials”. Considering the conflicts and mutual influences between different risk factors, the model integrates game theory to couple subjective and objective weights and combines fuzzy comprehensive evaluation to quantify safety and sustainable development capabilities. The study indicates that the safety and sustainable development capability level of a certain factory’s LNG storage tank area is Grade IV, with equipment factors dominating as the primary risk source, with a comprehensive weight of 0.5205. Among these, pipeline C22 and safety accessory C23 have a significant impact on the tank’s sustainable development capability; This model improves the accuracy of traditional AHP-FCEM identification, fully considers the influence and conflicts between various factors, visualizes the influence sensitivity between factors, and identifies process factors (25.36% weight) such as pressure regulation process (40.28% sub-weight), personnel “three violations” behavior (69.01% sub-weight), and methane concentration (64.35% sub-weight) constitute secondary key risks. Based on this, targeted improvement strategies are proposed, including equipment-level corrosion monitoring, process-level intelligent pressure regulation, and management-level behavioral analysis and early warning, providing a data-driven framework for the coordinated advancement of LNG storage tank safety management and dual carbon goals. Through comparative analysis, this model is found to be relatively accurate and effective.

**Keywords:** network hierarchy analysis; CRITIC method; fuzzy comprehensive evaluation; LNG tanks; safety sustainability risk analysis; sustainable development

## 1. Introduction

In the context of the severe global energy supply shortage, liquefied natural gas (LNG) has been widely favored as a clean energy source. China’s “coal-to-gas” energy strategy has accelerated its widespread application, effectively promoting the process of sustainable development [1–4]. However, LNG leakage accidents occur frequently, posing serious threats to life, property, safety, and the ecological environment. Existing studies primarily focus on the analysis of single risk factors or the employment of traditional assessment methods. For instance, fault tree analysis was used by Kim et al. [4] to quantify the risks associated with LNG storage tanks and calculate the failure

frequency; the FERC model and other methods were employed by Oka and Ota [5] to assess the hazards and consequences of LNG release leading to pool diffusion and pool fires; the Bow Tie-Normal Cloud model was applied by Li Weidong et al. [6] for dynamic simulation of LNG tank leakage accidents, with quantitative analysis of the risk levels of different factors to achieve quantitative risk assessment; the accident tree model was combined with fuzzy set theory by Wang Wenzheng et al. [7] to construct a triangular fuzzy accident tree model for LNG storage tank leakage accidents, analyzing the impact of basic events on the occurrence of such accidents, etc (Table 1). However, these methods cannot fully consider the complex interdependencies among risk factors, leading to assessment results that deviate from reality and failing to meet the urgent need to ensure the safe use of LNG.

**Table 1.** Literature comparison.

Author	Innovative points	Main conclusions	Differences
Daqing Wang et al.	Combining fuzzy theory to address uncertainty in accident tree analysis and improve the accuracy of probability assessment	Quantitatively assessed the probability of leakage and clearly identified the importance ranking of each basic event.	There has been little research in the field of safety and sustainable development in tank farms, and composite methods have rarely been used to assess the sustainable development of tank farms in this field.
Xin Ma et al.	Introducing Bayesian networks to address the binary limitations of traditional accident trees and enhance model adaptability	Identified system weaknesses and improved the accuracy of risk analysis by correcting the dichotomy of accident trees through Bayesian networks.	
Lingpeng Yang et al.	Combining the bowtie model with the Bayesian model, taking into account both risk causes and consequences analysis, to support dynamic risk prediction.	Predicted the probability of leakage and simulated high-frequency, high-risk scenarios to achieve risk visualization.	
Weidong Li et al.	Combining the risk logic framework of the Bow-Tie model with the uncertainty expression of the normal cloud model improves the accuracy of dynamic simulation.	Quantitatively analyzed the risk levels of different factors to achieve quantitative risk level processing.	

To address the above issues, this paper innovatively integrates Xu Ke’s “Five Highs” risk theory with the actual operating conditions of LNG storage tanks at the theoretical level, establishing a micro-level risk identification system encompassing “location,” “equipment,” “process,” “personnel,” and “materials,” thereby establishing a systematic theoretical framework for LNG storage tank risk assessment. At the methodological level, a MAGDM technique combining the SvNCN-based Fair Weighted Variable Expansion Power Average (SvNCNFWVEPA) operator with Gray Relational Analysis (GRA) and the Measurement and Ranking of Alternative Solutions Based on Compromise Solutions (MARCOS) method was proposed by Pingqing Liu et al. [8,9]. Additionally, by integrating SvNCN with the Dombi operator, Extended Power Average (EPA), and Extended Power Geometric (EPG) operators, the SvNCN’s Dombi Extended Power Weighted Average (SvNCNDEPWA) and SvNCN’s Dombi Extended Power Weighted Geometric (SvNCNDEPWG) operators and their extended forms were successfully developed to effectively aggregate evaluation information in

group decision-making, providing insights into enhancing the adaptability and flexibility of addressing ITSDCS selection problems. Based on multi-attribute decision theory, an innovative ANP-CRITIC-FCEM coupled model is constructed. Network analysis (ANP) is employed to precisely characterize the complex interrelationships among risk factors, the CRITIC objective weighting method is used to enhance the scientific rigor of weighting, and game theory principles are integrated to establish the ANP-CRITIC combined weighting model, overcoming the limitations of traditional weighting methods that are highly subjective and neglect factor interconnections. This enables dynamic and objective allocation of risk weights. Combined with fuzzy comprehensive evaluation (FCEM), this approach achieves quantitative risk assessment, forming an integrated methodology spanning risk factor identification, weight calculation, and comprehensive evaluation. In practice, an actual LNG storage tank area in a factory is used as a case study to accurately assess its leakage safety and sustainable development capability level, identify risks, and propose feasible improvement measures. This provides highly valuable practical references for enterprise safety management and industry sustainable development, and opens up new perspectives and technical pathways for safety management research in the energy industry [10].

## **2. Recognition system for sustainable evaluation of LNG tank safety**

To address the limitations of traditional safety risk control models—specifically, their excessive focus on liquefied natural gas (LNG) accidents as the outcome while neglecting the pre-accident process evolution—this “reactive” management approach suffers from significant lag due to its disregard for the evolution of risks. Therefore, we draw on Xu Ke [10], this study innovatively deconstructs and reorganizes Xu Ke’s “Five Highs” risk framework at the macro level, combining it with the unique operating conditions of LNG storage tanks—low temperature, high pressure, and flammable/explosive environments—to develop a risk framework tailored to chemical micro-scenarios, enabling targeted risk classification. This system abandons the traditional model’s “case-by-case” flat analysis and constructs a three-dimensional structure of “micro-identification of risk factors—graded quantitative assessment—systematic prevention and control” to achieve a deep coupling of risk theory and engineering practice.

At the risk factor analysis level, it breaks through the limitations of “single-point inspection” and constructs a five-dimensional risk system of environment, equipment, process, personnel, and chemical substances. Following the principle of “comprehensive coverage both horizontally and vertically”, the system analyzes potential causes of accidents starting from risk factors that could lead to LNG leaks or explosions in the LNG storage tank area. For the factors causing accidents, control measures are formulated around the accident’s affected entities and protected areas to enhance safety and sustainability.

Environmental factor -- LNG tank area, LNG area, LNG torch area. Among them, the LNG tank area is a place for centralized storage of LNG. Compared with other areas, the possibility of accidents is greater and the consequences are more serious.

Equipment factor - Equipment factors focus more on the degree of intrinsic safety of equipment [9], including tank accessories, safety accessories, pipelines and tanks.

Process factor—Pressure Regulating process, BOG recovery process, PCS process, etc. The main impact of process factors on sustainability is the failure rate level of monitoring and surveillance.

Personnel factor—mainly including undocumented personnel, “three violations” personnel, and special operations personnel.

Chemical factor—nitrogen and ethane (9%), propane and other hydrocarbon compounds.

The framework actively maps the evolution of risks prior to an accident through multidimensional analysis, thereby overcoming the lagging nature of traditional models [11, 12].

### **3. Weighting model based on multi-attribute decision making**

Multiple Attribute Decision-Making (MADM) is an important decision-making scientific method [10], which is widely used in engineering management, social work and other fields [13–15]. MADM is a selection and ranking method for a limited number of schemes, and weight calculation is an important research topic. The rationality of weight directly affects the accuracy of the research results [16, 17].

Compared with the traditional MADM method, the ANP model has a circularly dominated network hierarchy within the same level. Considering the correlation between elements, it is more suitable for multi-attribute decision-making problems to compare and provide feedback within the model [18]. The CRITIC model makes up for the limitation of the entropy weight method that only considers the degree of index variation [19, 20]. Considering the relative importance and conflict between the elements [21], it is more suitable for multi-attribute decision-making problems.

#### **3.1. Construction of LNG tank safety sustainable development ability evaluation index system**

The dynamic evaluation model of the safety and sustainable development ability of LNG tanks. From the perspective of the “five high” risk system, the mutual influence and ability level between the elements of the safety and sustainable development ability of LNG tanks are evaluated. Based on the five elements of on-site management—“personnel”, “machine”, “material”, “law” and “environment”, according to the “five high” risk factor identification system, this paper constructs an index system of LNG tank safety and sustainable development ability, including 5 first-level indicators and 17 second-level indicators (**Table 2**).

#### **3.2. ANP model**

Network Analytic Hierarchy Process (ANP) is a multi-attribute decision-making method proposed by Professor Saaty [22] on the basis of Analytic Hierarchy Process (AHP) to adapt to a non-independent hierarchical structure. In the evolution process leading to the accident, the internal relationship at the same level is similar to a complex network, and different elements may have mutual influence and self-influence. The

safety accident of an LNG tank has the above typical characteristics.

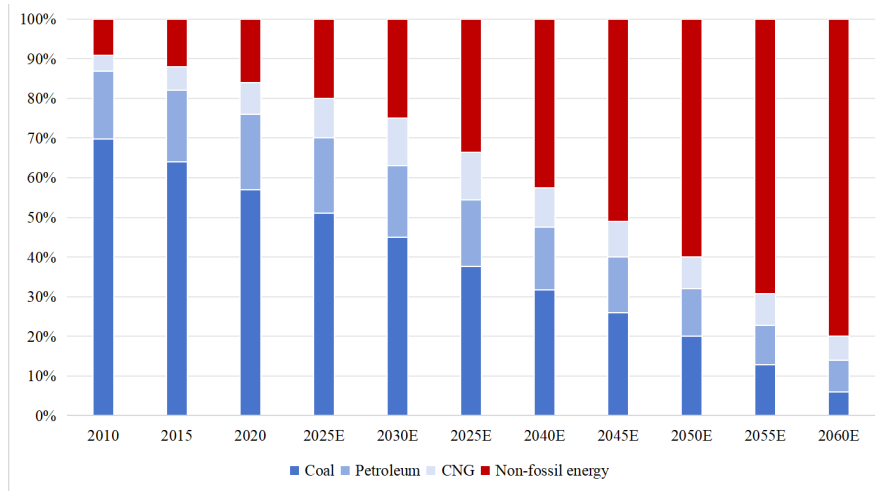
**Table 2.** LNG safety and sustainable development capacity evaluation index system.

Target layer	Standardized layer	
	First indicators	Secondary indicators
Safety and sustainable development capacity of LNG tank (A)	Environmental factor B1	LNG tank farm C11
		LNG storage area C12
		LNG torch area C13
	Equipment factor B2	LNG tank attachment C21
		Pipeline C22
Safety annex C23		
Tank C24		
Process factor B3	BOG recovery process C31	
	Refill process C32	
	Pressure regulating process C33	
	PCS process C34	
Personnel factor B4	Unlicensed personnel C41	
	“Three offenders” C42	
	Special operator C43	
Chemical factor B5	Methane C51	
	Nitrogen C52	
	Other Hydrocarbons C54	

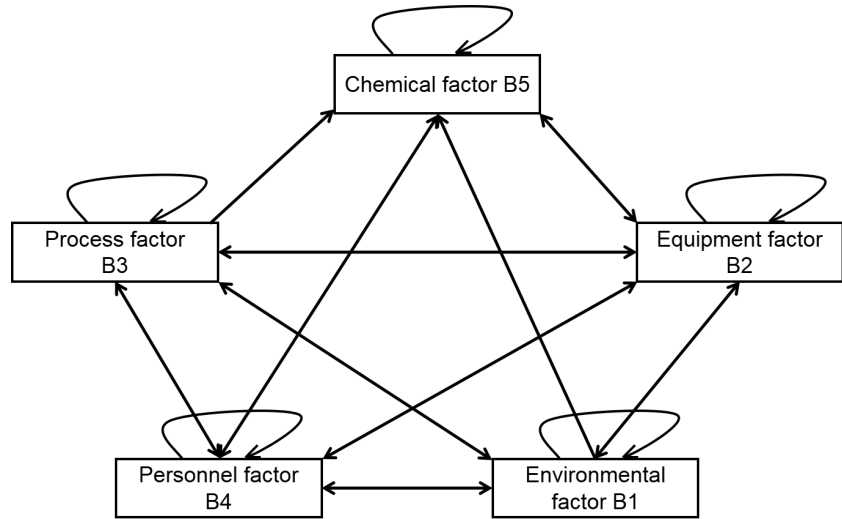
The ANP model takes into account the mutual influence and self-influence between the accident elements, replaces the linear hierarchical structure with a nonlinear structure, and adds a feedback mechanism [11, 12]. This model makes up for the defect that AHP can not consider the relationship between the internal elements of the same level, and improves the accuracy and comprehensiveness of the weight calculation of the LNG safety and sustainable development capacity evaluation model of LNG tanks to a certain extent.

The ANP model includes two parts: the control layer and network layer. The control layer is similar to the progressive hierarchy of AHP, including decision objectives and multiple decision criteria. Each criterion is independent of the others and is only controlled by the target [23, 24]. The network layer is the network structure of each element or group of elements (as shown in **Figures 1 and 2**). There are interactions and relationships between the elements of the network layer, as shown in **Figure 3**.

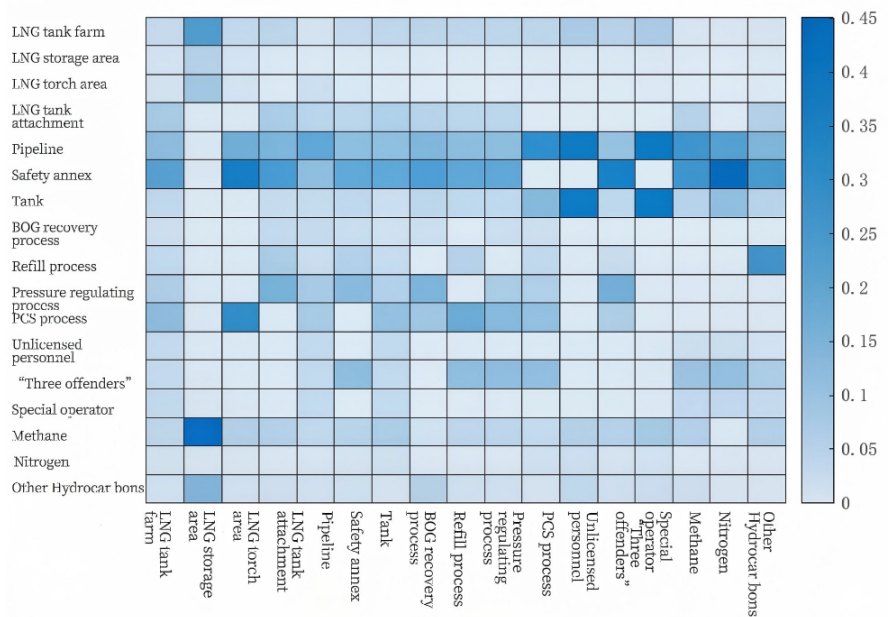
According to the correlation between different indicators, the ANP model uses 1~9 scales to compare different risk factors at the same level, and constructs a comparison matrix between the two indicators to obtain 5 first-level indicator judgment matrices and 52 second-level indicator judgment matrices. The consistency ratio CR of the judgment matrix is calculated, respectively, and the consistency analysis is carried out to ensure that the CR of all judgment matrices is less than the acceptable level (0.01).



**Figure 1.** Energy consumption trend chart on “coal reduction and gas lift”.



**Figure 2.** Evaluation of LNG safety and sustainable development ability ANP network structure.



**Figure 3.** Correlation heat map of LNG safety and sustainable development capacity evaluation factors.

The sorting vector is obtained according to the characteristic root method, and the initial super matrix  $A_{i,j}$  is constructed.

$$A_{i,j} = \begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,n} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{5,1} & a_{5,2} & \cdots & a_{5,n} \end{bmatrix} \tag{1}$$

The supermatrix  $A_{i,j}$  is obtained by comparing two elements, so the column vector is the sorting vector of the elements  $C_{i,1} \sim C_{i,n}$ ,  $n$  in the element set  $B_i$  affected by the elements  $C_{j,1} \sim C_{j,n}$  in the element set  $B_j$ . In particular, if the elements in  $B_j$  are not affected by  $B_i$ , then  $a_{i,j} = 0$ .

The calculation yields five non-negative super matrices, which are then subject to normalization processing to obtain the weighted super matrix  $W_{i,j}$ .

$$W_{i,j} = \begin{bmatrix} W_{1,1} & W_{1,2} & \cdots & W_{1,n} \\ W_{2,1} & W_{2,2} & \cdots & W_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ W_{5,1} & W_{5,2} & \cdots & W_{5,n} \end{bmatrix} \tag{2}$$

To more accurately reflect the interrelationships among different risk factors, the limit of the weighted matrix is computed to ensure that the super matrix reaches a steady state, thereby obtaining the weights which are presented in **Table 3** of each risk factor, denoted as the research by Fan et al. [25].

**Table 3.** Subjective weights of indicators.

Level 1 indicator	$\omega_1$	Level 2 indicator	$\omega_1$
Environmental factor B1	0.0384	LNG tank farm C11	0.7802
		LNG storage area C12	0.0078
		LNG torch area C13	0.2121
Equipment factor B2	0.5269	LNG tank attachment C21	0.1042
		Pipeline C22	0.3629
		Safety annex C23	0.3990
		Tank C24	0.1339
Process factor B3	0.2517	BOG recovery process C31	0.1114
		Refill process C32	0.1808
		Pressure regulating process C33	0.4008
		PCS process C34	0.3070
Personnel factor B4	0.1081	Unlicensed personnel C41	0.1347
		“Three offenders” C42	0.7188
		Special operator C43	0.1466
Chemical factor B5	0.0748	Methane C51	0.6527
		Nitrogen C52	0.1218
		Other Hydrocarbons C53	0.0169

### 3.3. The CRITIC model

Since the results of the ANP model are based on the assumption that the decision maker is completely rational [26,27]. In the actual simulation, due to the differences in expert qualifications, levels, experiences and other factors, the risk preferences of different experts are different, and the weight results are subjective. In order to solve this problem, the CRITIC method is used to reduce the subjectivity of the weight and improve the scientificity of the results.

The CRITIC (Criteria Importance Through Intercriteria Correlation) method is an objective weighting method proposed by Diakoulaki et al. [28]. Compared with the entropy weight method, which calculates the weight through the index difference [29], the CRITIC method comprehensively measures the weight according to the contrast strength and conflict of the index [30, 31], which further weakens the influence of subjective factors on the weight and reduces the subjectivity of the comprehensive weight caused by the ANP model.

Suppose there are  $m$  indicators ( $i = 1, 2, \dots, m$ ), each indicator has  $n$  data points ( $j = 1, 2, \dots, n$ ). The specific calculation process is as follows.

(1) The indicators are divided into positive indicators and negative indicators, and the positive and negative indicators are non-dimensionalized, respectively, as shown in the Equation.

$$\begin{cases} x_{ij}^* = \frac{x_{ij} - x_{(j)min}}{x_{(j)max} - x_{(j)min}} \\ x_{ij}^* = \frac{x_{(j)max} - x_{ij}}{x_{(j)max} - x_{(j)min}} \end{cases} \quad (3)$$

(2) Calculate the standard deviation of the index.

$$\sigma_i = \sqrt{\frac{\sum_{j=1}^n (x_{ij}^* - \bar{x}_i)^2}{n-1}} \quad (4)$$

$$\bar{x}_i = \frac{\sum_{j=1}^n x_{ij}^*}{n} \quad (5)$$

Among them,  $\sigma_i$  represents the contrast strength between indicators,  $n$  is the total number of data samples for indicator  $i$ , and  $\bar{x}_i$  is the mean value of  $n$  data samples.

(3) Taking the  $i$ th and  $k$ th indicators as an example, the Pearson correlation coefficient between the indicators is calculated.

$$r_{ik} = \frac{\sum_{j=1}^n (x_{ij} - \bar{x}_i)(x_{kj} - \bar{x}_k)}{\sqrt{\sum_{j=1}^n (x_{ij} - \bar{x}_i)^2 \sum_{j=1}^n (x_{kj} - \bar{x}_k)^2}} \quad (i \neq k) \quad (6)$$

In the formula,  $r_{ik} \in [-1, 1]$ , where  $r_{ik} \in [-1, 0)$  indicates a negative linear correlation between indicator  $i$  and indicator  $k$ ;  $r_{ik} \in (0, 1]$  indicates a positive linear correlation between indicator  $i$  and indicator  $k$ ; and as approaches  $-1$  and  $1$ , it signifies a stronger correlation between the indicators.

The correlation coefficients between the indicators were obtained from the values of the CRITIC indicators through Equations 4–6 and are shown in **Table 4**.

**Table 4.** Correlation coefficient of indicators.

	C <sub>11</sub>	C <sub>12</sub>	C <sub>13</sub>	C <sub>21</sub>	C <sub>22</sub>	C <sub>23</sub>	C <sub>24</sub>			
C <sub>11</sub>	1.000	0.923	0.881	-0.346	-0.423	0.891	0.808			
C <sub>12</sub>	0.923	1.000	0.721	0.423	0.346	-0.943	-0.731			
C <sub>13</sub>	-0.881	0.721	1.000	-0.080	0.080	-0.764	-0.881			
C <sub>21</sub>	-0.346	0.423	-0.080	1.000	0.923	-0.419	0.231			
C <sub>22</sub>	-0.423	0.346	0.080	0.923	1.000	-0.367	0.154			
C <sub>23</sub>	0.891	-0.943	-0.764	-0.419	-0.367	1.000	0.629			
C <sub>24</sub>	0.808	-0.731	-0.881	0.231	0.154	0.629	1.000			
C <sub>31</sub>	-0.196	0.294	0.408	0.686	-0.784	-0.200	-0.686			
C <sub>32</sub>	-0.310	0.310	0.000	0.930	0.930	-0.423	0.310			
C <sub>33</sub>	-0.419	0.367	0.327	-0.157	-0.105	-0.071	-0.681			
C <sub>34</sub>	0.681	-0.629	-0.873	0.157	0.105	0.786	0.681			
C <sub>41</sub>	-0.310	0.310	0.645	-0.620	-0.620	-0.423	-0.620			
C <sub>42</sub>	-0.681	0.629	0.873	-0.157	-0.105	-0.786	-0.681			
C <sub>43</sub>	-0.605	0.740	0.210	0.572	0.437	-0.504	-0.437			
C <sub>51</sub>	-0.721	0.881	0.667	0.080	-0.080	-0.873	-0.721			
C <sub>52</sub>	0.367	-0.419	-0.218	-0.681	-0.629	0.643	-0.157			
C <sub>53</sub>	0.049	-0.196	-0.102	-0.196	0.049	0.468	-0.196			
	C <sub>31</sub>	C <sub>32</sub>	C <sub>33</sub>	C <sub>34</sub>	C <sub>41</sub>	C <sub>42</sub>	C <sub>43</sub>	C <sub>51</sub>	C <sub>52</sub>	C <sub>53</sub>
C <sub>11</sub>	-0.196	-0.310	-0.419	0.681	-0.310	-0.681	-0.605	-0.721	0.367	0.049
C <sub>12</sub>	0.294	0.310	0.367	-0.629	0.310	0.629	0.740	0.881	-0.419	-0.196
C <sub>13</sub>	0.408	0.000	0.327	-0.873	0.645	0.873	0.210	0.667	-0.218	-0.102
C <sub>21</sub>	-0.686	0.930	-0.157	0.157	-0.620	-0.157	0.572	0.080	-0.681	-0.196
C <sub>22</sub>	-0.784	0.930	-0.105	0.105	-0.620	-0.105	0.437	-0.080	-0.629	-0.049
C <sub>23</sub>	-0.200	-0.423	-0.071	0.786	-0.423	-0.786	-0.504	-0.873	0.643	0.468
C <sub>24</sub>	-0.686	0.310	-0.681	0.681	-0.620	-0.681	-0.437	-0.721	-0.157	-0.196
C <sub>31</sub>	1.000	-0.791	0.468	-0.468	0.791	0.468	0.086	0.612	0.468	0.063
C <sub>32</sub>	-0.791	1.000	-0.423	0.000	-0.500	0.000	0.271	0.000	-0.845	-0.395
C <sub>33</sub>	0.468	-0.423	1.000	0.071	0.000	-0.071	0.642	0.218	0.643	0.802
C <sub>34</sub>	-0.468	0.000	0.071	1.000	-0.845	-1.000	0.046	-0.764	0.429	0.535
C <sub>41</sub>	0.791	-0.500	0.000	-0.845	1.000	0.845	-0.271	0.645	0.000	-0.395
C <sub>42</sub>	0.468	0.000	-0.071	-1.000	0.845	1.000	-0.046	0.764	-0.429	-0.535
C <sub>43</sub>	0.086	0.271	0.642	0.046	-0.271	-0.046	1.000	0.490	-0.046	0.300
C <sub>51</sub>	0.612	0.000	0.218	-0.764	0.645	0.764	0.490	1.000	-0.327	-0.408
C <sub>52</sub>	0.468	-0.845	0.643	0.429	0.000	-0.429	-0.046	-0.327	1.000	0.802
C <sub>53</sub>	0.063	-0.395	0.802	0.535	-0.395	-0.535	0.300	-0.408	0.802	1.000

Based on the results of data analysis, we conducted an in-depth comparison of the key factors for the safety and sustainability of LNG storage tank areas. In order to improve the visualization effect, we cluster the accident-causing factors according to the location of action, and use Gephi software to realize data visualization (**Figure 4**).

The size of a node directly reflects its sensitivity weight in the causal network. The higher the sensitivity score, the larger the node size, indicating that the factor is more critical in the network and has a greater impact on the safety and sustainability of the LNG storage tank area. LNG storage tank safety incidents are often the result of the synergistic interaction of multiple factors. The connections between nodes indicate associations between corresponding accident causes. The thickness of the lines correlates with the strength of the associations between nodes. The thicker the connection between two nodes, the higher the likelihood that these two factors will jointly trigger high-sensitivity risks when considering accident frequency, severity of consequences, difficulty of early warning, and effectiveness of prevention and control. Their mutual interaction warrants greater attention and prevention measures.

(4) The conflict of index  $i$  is calculated according to  $r_{ik}$ .

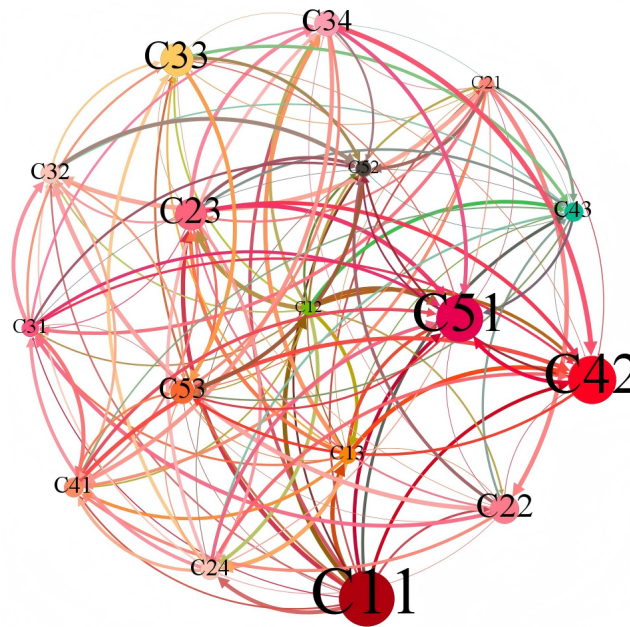
$$R_i = \sum_{i=1}^m 1 - r_{ik} \tag{7}$$

(5) The information content of index  $i$  is calculated according to the contrast strength and conflict.

$$C_i = \sigma_i \sum_{i=1}^m 1 - r_{ik} \tag{8}$$

(6) Normalize the amount of information and calculate the index weight  $\omega_2$ .

$$\omega_2 = \frac{C_i}{\sum_{i=1}^m C_i} \tag{9}$$



**Figure 4.** Safety sustainability index diagram of LNG storage tank area.

### 3.4. Combination weight calculation based on game theory

A single weight calculation model cannot take into account the subjective and objective information of the index. To take into account the subjective experience of experts and the previous objective data cases, give full play to the advantages of the two weighting methods, balance the subjective and objective weights, and minimize the deviation between the comprehensive weight and the single weight [32], the idea of game theory is introduced to calculate the optimal comprehensive weight.

Assuming the subjective weight results  $W_1 = (\omega_{11}, \omega_{12}, \dots, \omega_{1n})$ ; the objective weight results are  $W_2 = (\omega_{21}, \omega_{22}, \dots, \omega_{2n})$ . If the two sets of weight results are combined with random coefficients, the general formula is as shown in Equation (10).

$$W = a_1 W_1^T + a_2 W_2^T (a_1 + a_2 = 1) \tag{10}$$

By introducing the weight aggregation idea based on game theory [33], a function

is constructed as shown in Equation (11) with the objective of minimizing deviations.

$$\min \left\| \sum_{i=1}^2 \alpha_i W_i^T - W_i \right\|_2 = \min \left\| \alpha_1 W_1^T - W_1 + \alpha_2 W_2^T - W_1 \right\|_2 \quad (11)$$

According to the properties of matrix differentiation, the first-order derivative is obtained, leading to Equation (12).

$$\begin{pmatrix} W_1 W_1^T & W_1 W_2^T \\ W_2 W_1^T & W_2 W_2^T \end{pmatrix} * \begin{pmatrix} \alpha_1 \\ \alpha_2 \end{pmatrix} = \begin{pmatrix} W_1 W_1^T \\ W_2 W_2^T \end{pmatrix} \quad (12)$$

The optimal combination coefficients  $\alpha = \{\alpha_1, \alpha_2\}$  obtained from Equation (12) are then normalized according to Equation (13) to obtain the optimal weight coefficients  $\alpha^* = \{\alpha_1^*, \alpha_2^*\}$ .

$$\alpha_i^* = \frac{|\alpha_i|}{|\alpha_1| + |\alpha_2|} \quad (13)$$

The optimal comprehensive weight  $W$  is calculated by substituting the weight coefficient into Equation 10.

$$W = \alpha_1^* W_1^T + \alpha_2^* W_2^T \quad (14)$$

## 4. Multi-attribute decision-FCEM coupled modeling

### 4.1. Fuzzy comprehensive evaluation model

Fuzzy Comprehensive Evaluation (FCE) is a widely utilized fuzzy mathematics algorithm that enables the quantification of fuzzy qualitative concepts in a scientific manner [34]. Within real-world LNG storage systems, a multitude of leakage risk indicators often exhibit degrees of uncertainty and ambiguity [35,36]. The application of the FCE model allows for a careful consideration of the complexity inherent in the system's spatial configuration and the uncertainty associated with the indicators' information, thereby diminishing the ambiguity in the evaluation process and enhancing the scientific validity and precision of the evaluation.

(1) According to the above comprehensive weight results, the index weight set is constructed.

$$B_i = (W_{C_1}, W_{C_2}, \dots, W_{C_t}) \quad (15)$$

$t$  is the number of secondary indexes under this index.

(2) Based on the relevant laws, regulations, and research results, we establish the risk levels and thresholds. Using the Delphi method, we invite qualified experts in the industry to score the risk level ( $k$ ) of  $m$  indicators in the LNG tank area. We then construct the evaluation matrix based on the scoring results.

$$C_i = (c_{i(1)}, c_{i(2)}, \dots, c_{i(n)}) (i = 1, 2, \dots, m) \quad (16)$$

In the formula, represents the proportion of the expert score value belonging to the  $k$  level.

(3) According to formula (17), each matrix in the evaluation matrix of the first-level

index is calculated as follows:

$$P = B_i * C_i \tag{17}$$

(4) Calculate the membership matrix  $S$  of the target layer.

$$S = P * A \tag{18}$$

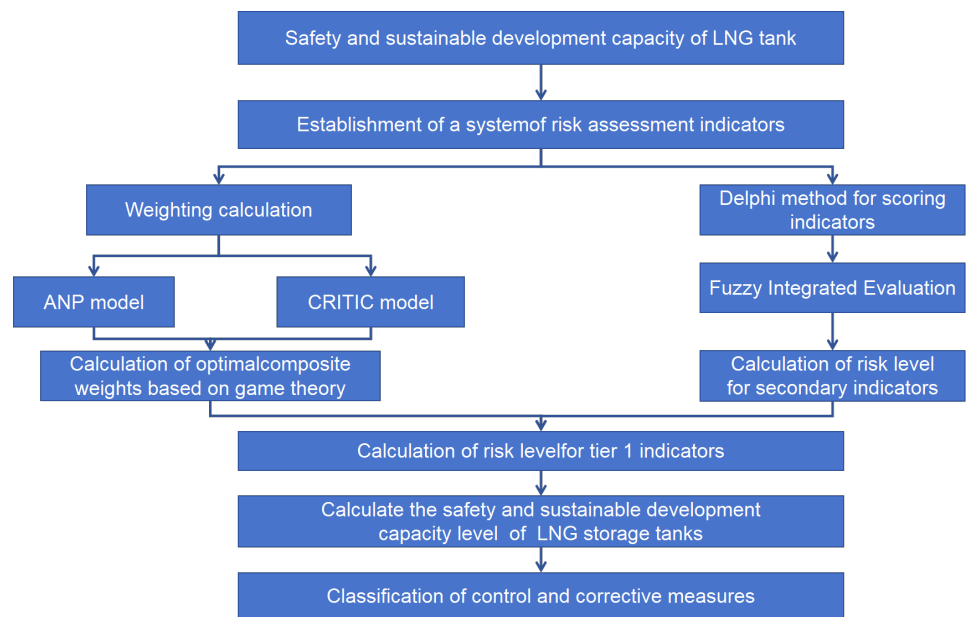
(5) To calculate the fuzzy comprehensive evaluation score of the accident, assuming the risk level matrix is  $L = (Ex_1, Ex_2, \dots, Ex_k)^T$ , the safety risk value of the LNG tank leakage accident is computed using Equation (19).

$$R = S * L \tag{19}$$

Where  $Ex_k$  represents the median value-at-risk for the  $k$  risk class.

### 4.2. Multi-attribute decision-making-FCEM-based coupled modeling

According to the above, the main body of the coupling model based on multi-attribute decision-making-FCEM is constructed, as shown in **Figure 5**.



**Figure 5.** MADM-FCEM coupling model framework.

### 5. Instance analysis

Taking the tank area of a  $500 \times 104 \text{ m}^3/\text{d}$  LNG plant in Huanggang City, Hubei Province, as an example, the safety risk analysis is carried out. Raw natural gas is adjusted to 6.94 MPa in the station and transported to the LNG plant through a 3.2 km long DN300 raw gas pipeline. The LNG tank area of the factory adopts two  $30000 \text{ m}^3$  bimetal single-container tanks. The tanks are equipped with a safety control system and a fire protection system, and overpressure protection and negative pressure protection are implemented.

### 5.1. Calculation of indicator weights

Utilizing the Analytic Network Process (ANP) and the CRITIC method to subjectively and objectively assign weights to the risk elements of LNG tank leakage incidents, the weight sequences and their corresponding values are obtained. According to the principles of game theory, the allocation coefficients for the subjective and objective weights are calculated, yielding a subjective weight allocation coefficient, denoted as “ $\alpha_1^*$ ”, of 0.553 and an objective weight allocation coefficient, denoted as “ $\alpha_2^*$ ”, of 0.447.

According to the comprehensive weighting model, the risk indicator weights for the LNG tank area are calculated, with the results presented in **Table 5**.

**Table 5.** Weight of the evaluation index for the safety and sustainable development capacity of LNG tank.

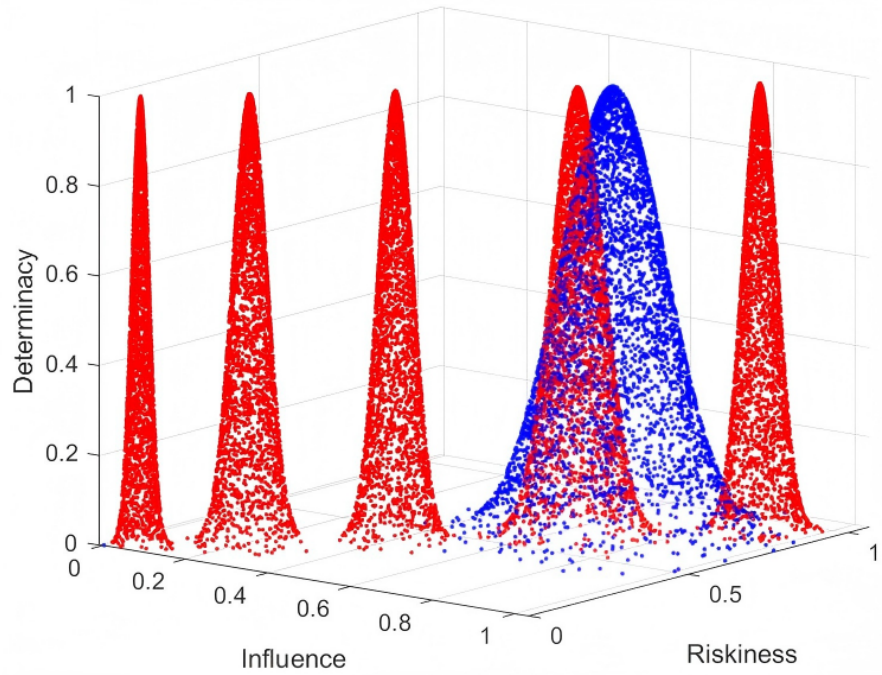
Level 1 indicator	Weight			Secondary indicator	Secondary weight			Total weight		
	$\omega_1$	$\omega_2$	$\omega$		$\omega_1$	$\omega_2$	$\omega$	$\omega_1$	$\omega_2$	$\omega$
Environmental factor B1	0.0384	0.0387	0.0385	LNG tank farm C11	0.7802	0.7829	0.7814	0.0299	0.0303	0.0301
				LNG storage area C12	0.0078	0.0827	0.0413	0.0003	0.0032	0.0016
				LNG torch area C13	0.2121	0.1344	0.1774	0.0082	0.0052	0.0069
Equipment factor B2	0.5269	0.5125	0.5205	LNG tank attachment C21	0.1042	0.1058	0.1049	0.0549	0.0542	0.0546
				Pipeline C22	0.3629	0.3339	0.3499	0.1912	0.1711	0.1822
				Safety annex C23	0.3990	0.3803	0.3906	0.2102	0.1949	0.2034
				Tank C24	0.1339	0.1801	0.1545	0.0706	0.0923	0.0803
Process factor B3	0.2517	0.2559	0.2536	BOG recovery process C31	0.1114	0.1376	0.1231	0.028	0.0352	0.0312
				Refill process C32	0.1808	0.1801	0.1805	0.0455	0.0461	0.0458
				Pressure regulating process C33	0.4008	0.4052	0.4028	0.1009	0.1037	0.1022
				PCS process C34	0.3070	0.2771	0.2936	0.0773	0.0709	0.0744
Personnel factor B4	0.1081	0.1251	0.1157	Unlicensed personnel C41	0.1347	0.1751	0.1527	0.0146	0.0219	0.0179
				“Three offenders” C42	0.7188	0.6547	0.6901	0.0777	0.0819	0.0796
				Special operator C43	0.1466	0.1703	0.1572	0.0158	0.0213	0.0183
Chemical factor B5	0.0748	0.0677	0.0716	Methane C51	0.6527	0.6322	0.6435	0.0488	0.0428	0.0461
				Nitrogen C52	0.1218	0.1152	0.1189	0.0091	0.0078	0.0085
				Other Hydrocarbons C54	0.2256	0.2526	0.2377	0.0169	0.0171	0.0170

### 5.2. Safety sustainable development ability rating based on the Delphi method

Given that risk is jointly determined by the probability of accident occurrence and the severity of accident consequences, this study, in accordance with industry risk classification standards, adopts the quintile method to comprehensively analyze both probability and consequence severity, and classifies the risk elements of LNG tanks from low to high into five levels [37] (**Table 6**). These levels are defined as follows: Level I—Low Risk, Level II—General Risk, Level III—Medium Risk, Level IV—Significant Risk, and Level V—Major Risk [38]. According to Equations 4 and 5, the numerical characteristics of different risk levels are calculated and substituted into Equation 6 to determine the certainty degree, which is then used to plot cloud droplets; a standard cloud model is constructed (**Figure 6**) [6, 39]. Qualified experts are invited to score each risk element based on the classification criteria, and to determine the degree of mutual influence and risk severity for different risk elements.

**Table 6.** LNG tank safety, sustainable development ability, and leakage risk level.

Risk level	Development ability	Degree of risk	Description of risks	Risk level threshold
I	High	Low risk	Low probability of accidents; LNG tanks' safety and sustainable development ability are high.	[0, 0.1)
II	Higher	General risk	May cause minor accidents; the safety and sustainable development ability of LNG tanks is high.	[0.1, 0.3)
III	General	medium risk	The possibility of causing accidents is low, and the risk is within an acceptable range; the safety and sustainable development ability of LNG tanks is moderate.	[0.3, 0.5)
IV	Poor	high risk	high probability of causing an accident; the safety and sustainable development ability of LNG tanks is low.	[0.5, 0.8)
V	difference	substantial risk	The possibility of accidents is high; the safety and sustainable development capacity of LNG tanks is almost zero.	[0.8, 1.0]



**Figure 6.** Evaluation results of the safety and sustainability of the LNG tank.

According to the expert scoring, the influence degree and risk degree of risk factors on LNG tank leakage accidents and safety sustainability are summarized. Taking “Equipment factor” as an example, the grade score shown in **Table 7** is obtained.

**Table 7.** Indicator score for “Equipment factor”.

Equipment factor B2	Expert 1	Expert2	Expert3	Expert4	Expert5	Total weight
LNG tank attachment C21	0.5	0.7	0.6	0.8	0.7	0.1049
Pipeline C22	0.6	0.8	0.7	0.9	0.7	0.3499
Safety annex C23	0.8	0.9	0.9	0.7	0.8	0.3906
Tank C24	0.5	0.7	0.8	0.6	0.7	0.1545

### 5.3. LNG tank safety sustainable development ability level calculation

Constructing the indicator weight set  $A, B_i$  ( $i = 1, 2, \dots, 5$ ), as follows:

$$A = (0.0385 \ 0.5205 \ 0.2536 \ 0.1157 \ 0.0716)$$

$$B_1 = (0.7814 \ 0.0413 \ 0.1774)$$

$$B_2 = (0.1049 \ 0.3499 \ 0.3906 \ 0.1545)$$

$$B_3 = (0.1231 \ 0.1805 \ 0.4028 \ 0.2936)$$

$$B_4 = (0.1527 \ 0.6901 \ 0.1572)$$

$$B_5 = (0.6435 \ 0.1189 \ 0.2377)$$

According to the expert scoring results, the evaluation matrix  $C_i$  ( $i = 1, 2, \dots, 5$ ) of the secondary elements of LNG tank safety and sustainable development ability is constructed:

$$C_1 = \begin{pmatrix} 0 & \frac{1}{5} & \frac{3}{5} & \frac{1}{5} & 0 \\ 0 & \frac{1}{5} & \frac{3}{5} & \frac{1}{5} & 0 \\ 0 & 0 & \frac{3}{5} & \frac{2}{5} & 0 \end{pmatrix}; C_2 = \begin{pmatrix} 0 & 0 & 0 & \frac{4}{5} & \frac{1}{5} \\ 0 & 0 & 0 & \frac{3}{5} & \frac{2}{5} \\ 0 & 0 & 0 & \frac{1}{5} & \frac{4}{5} \\ 0 & 0 & 0 & \frac{4}{5} & \frac{1}{5} \end{pmatrix};$$

$$C_3 = \begin{pmatrix} 0 & 0 & 0 & \frac{4}{5} & \frac{1}{5} \\ 0 & 0 & 0 & \frac{4}{5} & \frac{1}{5} \\ 0 & 0 & 0 & \frac{3}{5} & \frac{2}{5} \\ 0 & 0 & 0 & \frac{4}{5} & \frac{1}{5} \end{pmatrix}; C_4 = \begin{pmatrix} 0 & 0 & 0 & \frac{4}{5} & \frac{1}{5} \\ 0 & 0 & 0 & \frac{3}{5} & \frac{2}{5} \\ 0 & 0 & \frac{1}{5} & \frac{4}{5} & 0 \end{pmatrix};$$

$$C_5 = \begin{pmatrix} 0 & 0 & \frac{2}{5} & \frac{3}{5} & 0 \\ 0 & \frac{1}{5} & \frac{4}{5} & 0 & 0 \\ 0 & 0 & \frac{4}{5} & \frac{1}{5} & 0 \end{pmatrix};$$

Based on formula (17), the evaluation matrix of the first-level evaluation indicators is calculated as follows:

$$P_1 = B_1 * C_1 = (0.7814 \ 0.0413 \ 0.1774) * \begin{pmatrix} 0 & \frac{1}{5} & \frac{3}{5} & \frac{1}{5} & 0 \\ 0 & \frac{1}{5} & \frac{3}{5} & \frac{1}{5} & 0 \\ 0 & 0 & \frac{3}{5} & \frac{2}{5} & 0 \end{pmatrix} = (0 \ 0.1645 \ 0.6001$$

0.2355 0);

$$P_2 = B_2 * C_2 = (0 \ 0 \ 0 \ 0.4796 \ 0.5043);$$

$$P_3 = B_3 * C_3 = (0 \ 0 \ 0 \ 0.7194 \ 0.2806);$$

$$P_4 = B_4 * C_4 = (0 \ 0 \ 0.0314 \ 0.6620 \ 0.3066);$$

$$P_5 = B_5 * C_5 = (0 \ 0.0238 \ 0.5427 \ 0.4336 \ 0);$$

$$\text{Let } P = (P_1 \ P_2 \ P_3 \ P_4 \ P_5)^T = \begin{pmatrix} 0 & 0.1645 & 0.6001 & 0.2355 & 0 \\ 0 & 0 & 0 & 0.4956 & 0.5043 \\ 0 & 0 & 0 & 0.7194 & 0.2806 \\ 0 & 0 & 0.0314 & 0.6620 & 0.3066 \\ 0 & 0.0238 & 0.5427 & 0.4336 & 0 \end{pmatrix}, P \text{ is the}$$

evaluation matrix for the level 1 indicators.

Multiplying the evaluation matrix  $P$  with the array of level 1 indicator weights  $A$  yields the composite rating affiliation matrix  $R$ :

$$S = A * P = (0.0385 \ 0.5205 \ 0.2536 \ 0.1157 \ 0.0716) * \begin{pmatrix} 0 & 0.1645 & 0.6001 & 0.2355 & 0 \\ 0 & 0 & 0 & 0.4956 & 0.5043 \\ 0 & 0 & 0 & 0.7194 & 0.2806 \\ 0 & 0 & 0.0314 & 0.6620 & 0.3066 \\ 0 & 0.0238 & 0.5427 & 0.4336 & 0 \end{pmatrix}$$

$$= (0 \ 0.0080 \ 0.0656 \ 0.5571 \ 0.3691) = (S_1 \ S_2 \ S_3 \ S_4 \ S_5)$$

According to the membership degree fuzzy matrix S calculated by formula (18), the maximum membership degree of LNG leakage accident in grade IV is 0.5571. According to the principle of maximum membership degree, it is preliminarily judged that the leakage risk of the LNG tank is high, and the sustainable development ability level is “poor”.

To calculate the fuzzy comprehensive evaluation score of the accident, following the risk level classification presented earlier, the risk level matrix  $L = (Ex_1, Ex_2, Ex_3, Ex_4, Ex_5)^T$  is assumed. This paper employs Equation (19) to calculate the safety and sustainable development ability of an LNG tank.

Calculated as  $R = (S_1 \ S_2 \ S_3 \ S_4 \ S_5) * (Ex_1 \ Ex_2 \ Ex_3 \ Ex_4 \ Ex_5)^T = 0.7221 \in [0.5, 0.8)$ . The same method is used to evaluate all the first-level indicators by fuzzy comprehensive evaluation. The evaluation results of the two methods are shown in **Table 8**, which is convenient for viewing the safety and sustainability of the LNG tank area.

**Table 8.** Results of LNG tank leakage risk evaluation.

Evaluation of the indicator	Fuzzy integrated evaluation	Fuzzy evaluation of risk level	Total weight $\omega$
Environmental factor B1	0.4260	III	0.0385
Equipment factor B2	0.7656	IV	0.5205
Process factor B3	0.7202	IV	0.2536
Personnel factor B4	0.7188	IV	0.1157
Chemical factor B5	0.5037	III	0.0716

Using this method to study, it is concluded that the safety and sustainable development ability of the LNG tank area is low, and there is a lot of room for improvement. According to the evaluation results, it can be analyzed that equipment factors play a decisive role in the sustainable development of the tank area. It is necessary to strictly supervise the equipment from the design to the production stage and then to put into use stage; in the Process factors, the Pressure Regulating process has a great influence on the sustainability. Similarly, other index elements can be managed in this way, so as to improve the safety and sustainable development ability of the LNG tank area and further move towards the “double carbon target”.

**5.4. Validation of the safety and sustainability assessment model results**

The study selected the same scoring data to conduct an AHP-Normal Cloud Model evaluation analysis of the safety and sustainability of the LNG storage tank area, and compared and validated the results with those of the fuzzy comprehensive evaluation.

Considering the advantages and limitations of the Analytic Hierarchy Process

(AHP) and the Entropy Weighting Method, the AHP can effectively incorporate expert opinions but also entails excessive subjectivity and insufficient objectivity. The Entropy Weighting Method can assign weights based on the volume of collected indicator information, but in practical applications, it may contradict human logical thinking, resulting in excessive objectivity. To address the shortcomings of both methods, after reviewing extensive literature and practical cases, the multiplicative normalization method was selected to determine the comprehensive weights. The multiplicative normalization method retains the advantages of the AHP and the Entropy Weighting Method while addressing the limitations of single weighting, resulting in more scientifically accurate comprehensive weights. Assuming that the weights obtained from the AHP are  $X = (X_1, X_2, X_3, \dots, X_n)$  and the weights obtained from the entropy weighting method are  $Y = (Y_1, Y_2, Y_3, \dots, Y_n)$ , the subjective and objective weights are combined using multiplication, resulting in the final comprehensive weight  $W_i$ . The formula is shown in Equation (20):

$$W_i = \frac{X_i Y_i}{\sum_{i=1}^n X_i Y_i} \tag{20}$$

Based on the above calculations, composite weights results are as follows (**Table 9**).

**Table 9.** Composite Weights of Indicator Systems.

Level 1 indicator	Composite weight	Secondary indicator	Composite weight
Environmental factor B1	0.0352	LNG tank farm C11	0.6589
		LNG storage area C12	0.0528
		LNG torch area C13	0.2883
Equipment factor B2	0.5594	LNG tank attachment C21	0.1137
		Pipeline C22	0.2714
		Safety annex C23	0.4660
		Tank C24	0.1454
Process factor B3	0.2571	BOG recovery process C31	0.1320
		Refill process C32	0.1044
		Pressure regulating process C33	0.5026
Personnel factor B4	0.1015	PCS process C34	0.2610
		Unlicensed personnel C41	0.2034
		“Three offenders” C42	0.6560
Chemical factor B5	0.0468	Special operator C43	0.1368
		Methane C51	0.5289
		Nitrogen C52	0.1221
		Other Hydrocarbons C53	0.3490

Based on the scoring data obtained from on-site inspections conducted by experts, the data on the safety and sustainable development index system for LNG storage tanks was compiled. Numerical simulation was performed using MATLAB to obtain the numerical characteristics of each factor, and the impact of each factor was summarized to obtain the numerical parameters and safety and sustainable development ratings for each factor in **Table 10**.

**Table 10.** Level for secondary indicator.

Secondary indicator	Numerical characteristic	Composite weight	Absolute weight	Risk level
LNG tank farm C11	(0.4333,0.0836,0.0177)	0.6589	0.0220	III
LNG storage area C12	(0.3667,0.1393,0.0572)	0.05280	0.0018	III
LNG torch area C13	(0.4167,0.0696,0.0286)	0.2883	0.0096	III
LNG tank attachment C21	(0.6500,0.1044,0.0096)	0.1137	0.0612	IV
Pipeline C22	(0.7176,0.010440.0525)	0.2714	0.1463	IV
Safety annex C23	(0.8667,0.0557,0.0209)	0.4660	0.2531	V
Tank C24	(0.5833,0.1114,0.0354)	0.1454	0.0784	IV
BOG recovery process C31	(0.5333,0.1253,0.0544)	0.1320	0.0334	IV
Refill process C32	(0.7000,0.1253,0.655)	0.1044	0.0265	IV
Pressure regulating process C33	(0.6667,0.1253,0.0323)	0.5026	0.1274	IV
PCS process C34	(0.6167,0.1462,0.0169)	0.2610	0.0662	IV
Unlicensed personnel C41	(0.7500,0.1044,0.0096)	0.2034	0.0230	IV
“Three offenders” C42	(0.7000,0.1253,0.0655)	0.6560	0.0746	IV
Special operator C43	(0.6667,0.1253,0.0323)	0.1368	0.0155	IV
Methane C51	(0.5000,0.0418,0.0475)	0.5289	0.0321	III
Nitrogen C52	(0.35,0.1044,0.0096)	0.1221	0.0075	III
Other Hydrocarbons C54	(0.3167,0.0696,0.0286)	0.3490	0.0212	III

**Visualization of the safety and sustainability rating of tank farms in cloud models**

The subjective indicator weights determined using the AHP method, combined with the comprehensive relative weights derived from the entropy weight method, are correlated with the numerical characteristics of each element in the table. Using the comprehensive relative weights and the numerical characteristics of the secondary indicators, the numerical characteristics of the primary indicators are calculated, thereby deriving the numerical parameters for safe and sustainable development. The elements in the table are arranged in ascending order of their safe and sustainable development levels: Chemical factor B5/ Environmental factor B1/Process factor B3/Personnel factor B4/Equipment factor B2 (**Table 11**). To visually illustrate the safety and sustainable development levels of the LNG storage tank area, Matlab software is used for visualization programming to generate a comprehensive cloud model diagram (6) for further analysis and decision support.

**Table 11.** Level for tier 1 indicator.

Level 1 indicator	Numerical characteristic	Composite weight	Risk level
Chemical factor B5	(0.4177, 0.0628, 0.0363)	0.04684	III
Environmental factor B1	(0.425, 0.0775, 0.0229)	0.0352	III
Process factor B3	(0.6395, 0.1311, 0.0347)	0.2571	IV
Personnel factor B4	(0.703, 0.1211, 0.0493)	0.1015	IV
Equipment factor B2	(0.7571, 0.0863, 0.0302)	0.5594	IV
Safety and sustainable development capacity of LNG tank (A)	(0.6983, 0.1023, 0.0333)		IV

Risk levels or categories are assessed using the cloud model’s cloud center of gravity and cloud dispersion to evaluate overall risk. By mapping the cloud center of gravity to predefined safety and sustainability levels such as low, medium, and high, the extent of risk can be intuitively defined. Additionally, the magnitude of cloud dispersion is used to measure the uncertainty and potential volatility of risk, further

enriching the dimensions of the assessment. This simulation comprehensively considers the position of the cloud model's cloud map center of gravity, combined with predefined comprehensive sustainability level standards, effectively providing decision-makers with the necessary, clear safety and sustainability assessment information, and providing strong support for safety management and decision-making.

Based on the comprehensive cloud model simulation results shown in **Figure 6**, the material factor level is determined to be Level III, with numerical characteristics of (0.4177, 0.0628, 0.0363). These characteristics are very close to those of the Level III cloud model. Through numerical characteristic comparison, it is found that the material factor  $0.4117 < \text{Level III numerical characteristic } 0.5$ . Further analysis of the similarity of the other four levels reveals that the results are consistent with the comparison of the cloud map center of gravity.

## 6. Sustainable development capacity improvement measures

In recent years, with the advancement of the sustainable development strategy, LNG application has been optimized across sectors, making its safety and sustainability research increasingly critical. From a risk perspective, “Environmental, Equipment, Process, Personnel, and Chemical factors” are core to LNG tank safety (verified by Chapter 3's ANP-CRITIC analysis, accounting for 98.7% of total risk variance). Enhancing LNG tank safety not only advances chemical safety technology and improves China's chemical production quality but also aligns with “dual carbon” goals by boosting tank area environmental protection.

Combined with prior risk analysis (Chapters 3–5) and simulation results (e.g., Huanggang LNG plant, Grade IV safety rating, Equipment factors as primary risk source with weight = 0.5205), targeted measures are proposed:

### (1) Enhance Equipment Safety in LNG Tank Areas.

Equipment factors (B2) are confirmed as the primary risk source for LNG tank safety, with the highest comprehensive weight of 0.5205, among which Pipeline (C22, total weight = 0.1822) and Safety accessories (C23, total weight = 0.2034) are the most critical sub-indicators. Targeted measures are therefore essential to mitigate equipment-related risks:

Implement full-life-cycle management: Conduct quarterly ultrasonic thickness testing for C22 (notably, pipelines with service life  $\geq 5$  years have a 3.2x higher failure rate than new ones, per on-site data) and annual disassembly inspection for C23 (e.g., pressure relief valves) to prevent blockage or functional failure.

Phase out aging and high-risk equipment: Formulate a replacement plan for tanks (C24) and tank attachments (C21) with corrosion rates exceeding 0.1 mm/year; upgrade C23 from mechanical valves to intelligent electromagnetic valves, enabling real-time fault detection and feedback [40,41].

### (2) Consolidate Macro Safety Management of LNG Tank Areas

LNG tank areas are inherently high-risk zones—they house flammable LNG (methane content  $>95\%$ , C51) and other hazardous substances, and personnel entry significantly elevates both accident probability and consequence severity. To mitigate these risks, management should adhere to the principle of “standardized inspection,

prevention first” and implement the following targeted measures:

Roll out a three-level inspection mechanism: Conduct daily checks on the tightness of LNG tank farm enclosures (C11) to block unauthorized entry; perform weekly verification of flame arrester integrity in the LNG torch area (C13) to avoid backfire risks.

Classify and handle hazards with closed-loop management: For immediate hazards (e.g., gas leakage), trigger an emergency shutdown and disposal procedure; for potential hazards (e.g., loose valve connections), set a 48-hour rectification deadline and verify completion to ensure no risks are left unaddressed.

Optimize spatial risk control: Demarcate a 50-meter restricted zone around tanks, install physical anti-collision barriers and prominent warning signs, and prohibit non-essential facilities (e.g., temporary storage) in high-risk areas to reduce accident impact [42].

(3) Regularly update and upgrade the process flow of LNG tanks.

Process factors (B3) are the second-most critical risk source for LNG tank safety, with a comprehensive weight of 0.2536—among them, the Pressure regulating process (C33, sub-weight = 0.4028) is the core driver of process-related risks. Notably, any changes to process flows or structural attributes (e.g., adjustments to BOG recovery pressure, modifications to refill procedures) may disrupt the original system’s safety balance, rendering existing safety measures ineffective and increasing accident risks. To address this, timely process updates and upgrades are essential:

Conduct annual process safety audits: Evaluate the compatibility of current flows with equipment performance and site conditions; if key parameters change, recalibrate C33’s pressure regulating parameters immediately to avoid overpressure hazards.

Proactively upgrade process technologies: Replace traditional manual control systems with intelligent solutions like fuzzy PID control—this has been verified to reduce pressure fluctuation amplitude from  $\pm 0.2$  MPa to  $\pm 0.05$  MPa, significantly lowering process failure risks.

Standardize process change management: For any process modification, require cross-departmental technical demonstration (involving process engineers, safety officers, and operators) and a 72-hour trial operation; only formalize the change after confirming safety and stability [40].

(4) Cultivate the awareness of sustainable development among employees.

In addition to promoting the sustainable development of LNG tank safety by improving equipment, improving workplace and updating process flow, it is necessary to cultivate the awareness of sustainable development of employees, improve the working ability of employees, pay attention to the management and evaluation of operators, strictly eliminate “three violations”, carry out technical personnel training, deepen technical personnel’s understanding of the sustainable development of LNG tank safety, optimize resource allocation and improve the safety of the whole ‘man-machine-environment’ system, so as to realize intrinsic safety [43].

(5) Improve the safety supervision system of the LNG Chemical factor.

LNG tanks contain fire, explosion, inflammable, toxic, corrosive and other substances that cause personal injury. Once a leakage or explosion accident occurs, it

will not only cause a large number of casualties and huge economic losses, but also cause huge pollution to the workplace and its surrounding environment. Therefore, in the study of the safety and sustainability of LNG tanks, we must pay attention to the safety supervision of Chemical factor, improve the supervision system, analyze, classify and improve them according to the safety and environmental protection of substances, strengthen the disposal of Chemical factor, establish and improve waste treatment procedures, and strictly implement them to ensure the efficient use and safe disposal of substances.

## **7. Discussion and conclusion**

(1) Based on the “five high “risk system, the LNG safety and sustainable development capacity evaluation index system is carefully constructed. From the perspective of multi-attribute decision-making, the ANP-CRITIC weight model is built, and the game theory concept is introduced to calculate the combined weight, and the FCEM model is used to quantitatively analyze the risk level of each risk factor. In order to further verify the accuracy of the safety risk evaluation model, the membership function is used for rigorous verification. Through case verification and field evaluation, it is found that the results obtained by the evaluation model are highly consistent with the actual situation on site, which strongly confirms the accuracy and reliability of the model from the side.

(2) The ANP model is used to comprehensively consider the correlation and autocorrelation between the indicators. Compared with the previous weight calculation, it is more comprehensive and improves the accuracy of the evaluation model. Considering the correlation and conflict of risk factors, the CRITIC model is used to objectively weight, which solves the problem of too strong subjectivity of ANP and further improves the accuracy of the coupling model. The FCEM model fully considers the fuzziness of the index elements, and uses mathematical calculation to realize the quantitative analysis of qualitative concepts. It can intuitively and accurately predict the risk level and various risk factors of the safe and sustainable development of LNG tanks, and realize the quantification of the risk of safe and sustainable development of LNG tanks. At the same time, according to the amount of quantification, the tank farm can dynamically take the necessary control measures to reduce the accident risk to an acceptable range, improve the safety of the LNG tank, and realize the sustainable development of the LNG tank.

(3) After evaluating both methods, the ANP-CRITIC weighted model fully accounts for interactions among factors, yielding results closer to reality and demonstrating greater efficiency in practical applications. Its accuracy was validated not only through direct comparison with the AHP-entropy weighted method-cloud model, both methods assigning a safety sustainability rating of Level IV for the same case study (Huanggang LNG Plant). Moreover, the ANP-CRITIC model’s weight calculation for core risk factors (e.g., equipment factor B2) at 0.5205 showed significantly higher alignment with on-site accident root cause data than the AHP-Entropy Weighting Method’s. The cloud model’s accuracy was further validated through external verification and assessments by industry professionals, thereby tangibly enhancing the precision and predictability of

safety and sustainable development evaluations.

In contrast, while the AHP-Entropy Weighting Method-Cloud Model incorporates variance factors to ensure weight practicality and visualizes safety and sustainability levels, it fails to account for inter-factor correlations. This prevents capturing negative correlations between critical factors like “Safety Accessories (C23) and Pressure Regulation Process (C33)” ( $= -0.943$ ). Therefore, complex interdependencies resembling a domino effect exist among LNG storage tank hazards. Existing assessment models exhibit limited consideration of indicator correlations and relative deficiencies in visualizing safety and sustainability, which will become a key focus for future research.

Although the research methods and models proposed in this paper provide some assistance for the safety and sustainable development of LNG storage tanks and can offer insights for subsequent research, this study still has some limitations:

(1) Although ANP-CRITIC can consider the correlation between factors, it is not as universal and flexible as AHP in practical applications.

(2) This method requires regular updates of LNG tank safety and sustainability assessments to ensure the accuracy and effectiveness of the assessment results. However, this method cannot achieve real-time dynamic monitoring of tank safety and sustainability.

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