Fuzzy Comprehensive Hierarchical Evaluation Model for Lightning Disaster in Oil Storage Depots

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Abstract. An oil storage depot is one of the most dangerous places in the petrochemical industry. Lightning strikes present a significant risk to the regular operation of oil storage depots and the safety of the staff. This paper established a lightning disaster risk model using practical evaluation techniques to provide insight into the lightning disaster prevention methods used in oil storage depots both domestically and abroad. The risk assessment of lightning disaster in oil storage depots was performed according to this model, after which the risk index factors were classified. Furthermore, this paper reasonably resolved the problems surrounding the limited use of lightning protection standards and the challenge in quantifying the qualitative factors during lightning disaster risk assessment in oil storage depots. This references the risk assessment of lightning disaster in oil storage depots and the related lightning protection design.

1. Introduction
An oil depot serves as the distribution center for flammable and volatile oil products. According to the national standards and industry specifications, an oil depot must implement fire prevention, explosion-proof, and other safety measures, while lightning protection, anti-static, and ground potential counterattack consideration is essential [1]. In particular, lightning disaster risk assessment is crucial for mitigating the risk in large oil reserve depots emitting significant energy. IEC62305-2 denotes the mainstream lightning disaster risk assessment system. This system considers single buildings and service facilities as the evaluation objects, assessing lightning disaster risk via its potential to cause economic, cultural, service, and life loss to improve preventative measures. However, the system does not solve the problem of lightning risk assessment of buildings and regions. The urgent evaluation of regional and high-risk oil storage depots is crucial for practical applications. Therefore, this paper examines the fuzzy comprehensive hierarchical evaluation model for lightning disaster in oil storage depots, which is essential for lightning prevention in oil storage depots.

Various mathematical methods have been used both domestically and abroad to analyze the risk of lightning disaster, including the Monte Carlo method, fuzzy mathematics, and the analytic hierarchy process. Necci, Amos et al. [2-5] proposed a quantitative method to evaluate the damage probability of lightning strike equipment. The probability distribution function of the peak current intensity and the lightning charge was used to quantify the lightning intensity. The expected frequency and damage
probability of the lightning equipment were determined using Monte Carlo simulation, while an equipment damage model of the metal perforation in lightning was also reproduced. Elisabetta Renni et al. [6] studied the damage and release modes of equipment under lightning impulse. After a lightning strike, the damage state and expected release level were determined by establishing a specific post-release event tree, highlighting the risk of a possible lightning strike during a rainstorm. The ignition probability of the released flammable substances was estimated according to the analytical data. A. Borghetti et al. [7] used the Monte Carlo method to calculate the estimated annual damage caused by metal melting due to direct lightning strike events. Gallego, Luis E, et al. [11] proposed using the fuzzy mathematics method to quantify and qualify the uncertain factors during lightning disaster risk assessment while analyzing the damage risk posed by lightning and determining the frequency and intensity of the lightning phenomenon.

By applying the fuzzy mathematics theory to analyze the causative disaster factors, the environmental carrying sensitivity, and the vulnerability of the disaster bearing body, Yu Shuyu, Wang Shuyi, Feng He et al. [8-10] proposed a corresponding lightning risk assessment structure. Hu Haibo, Yuan Xiangling, Zhu Xuanru et al. [12-14] used the analytic hierarchy process to determine the weight distribution of the evaluation index, establish the corresponding hierarchical model, and divide the evaluation area into different areas with the degree of risk arranged from high to low. Considering the oil storage depots as the evaluation object and adopting the analytic hierarchy process, Li, Chen et al. [15,16] proposed a lightning risk assessment model, determined the index weight, and used the fuzzy comprehensive algorithm to calculate the lightning risk index in the region, obtaining the corresponding lightning risk and the safety levels of different factors.

Many factors can affect the risk assessment of lightning disasters and lightning protection measures of oil storage depots. More accurate assessment requirements necessitate more complex methods, increasing the implementation difficulty of the project. Although the methods mentioned above are rational and quantitative for the risk assessment of lightning disaster, some aspects should be further verified and improved. Although the Monte Carlo method can calculate the probability of different kinds of disasters and accidents caused by lightning, it typically involves a single accident scene, and a suitable evaluation system for high-risk, complex objects like an oil storage depot has yet to be completed. The assessment method based on fuzzy mathematics and the analytic hierarchy process can effectively combine the qualitative and quantitative assessment of lightning disaster risk. Although it has certain objective practicability, it also exhibits some shortcomings. Fuzzy mathematics can only divide the risk area of the assessment object and cannot define the risk degree of each assessment index. In addition, there is a certain subjectivity in the expert scoring method of the analytic hierarchy process, which should be combined with the case to optimize the score division method while reasonably certifying the index weight.

2. The lightning disaster risk model based on the analytic hierarchy process

2.1. The hierarchical model for lightning disaster risk assessment for oil storage depots

The hierarchical model for the lightning risk evaluation of oil storage depots was constructed by combining the analytic hierarchy process with the lightning strike risk, safety evaluation index system. Target layer A: Lightning disaster risk A of oil storage depots. Criteria layer B: Lightning risk B1, disaster bearing body risk B2, regional risk B3, and defense risk B4. Sub criteria layer C: Lighting current intensity C1, annual thunderstorm day C2, lightning density C3, thunderstorm path C4, project attributes C5, tank characteristics C6, instrument electrical system C7, soil conditions C8, topography C9, surrounding environment C10, sealing device form C11, equipotential bonding C12, and grounding resistance C13. Index layer D: Number of personnel D1, oil depot grade D2, floor area D3, oil risk D4, combustible gas concentration D5, instrument system D6, electrical system D7, soil resistivity D8, vertical soil stratification D9, horizontal soil stratification D10, relative height D11, safety distance D12, and electromagnetic environment D13. The specific hierarchical model is shown in Figure 1.
2.2. The construction of the judgment matrix and the relative weight analysis
Constructing the judgment matrix is a crucial step in quantifying each index, while the importance of all factors in the same layer can be determined via pairwise comparison. The judgment matrix was constructed using the 1~9 scale method, combined with the actual project site situation, relevant standards, and the experience of relevant experts. The factors of each criterion layer were compared to determine their relative importance and provide the corresponding ratios [16].

The constructed judgment matrix \( A \) is as follows:

\[
A = (a_{ij})_{n \times n} =
\begin{bmatrix}
  a_{11} & a_{12} & \cdots & a_{1n} \\
  a_{21} & a_{22} & \cdots & a_{2n} \\
  \vdots & \vdots & \ddots & \vdots \\
  a_{n1} & a_{n2} & \cdots & a_{nn}
\end{bmatrix}
\]

(1)

\( A_i \) refers to the indicators at the same level belonging to the same index \( X \) at the upper level, where

\( a_{ii}=1, \ a_{ji}=1/a_{ij}, \ i=(1, 2, \ldots, n). \)

According to the constructed judgment matrix, the relative weight of each index in each criterion layer is primarily calculated using the following formula:

\[
AW = \lambda_{\text{max}}W
\]

(2)

where \( \lambda_{\text{Max}} \) is the largest eigenvalue of the judgment matrix \( A \), and \( W \) is \( \lambda_{\text{Max}} \) corresponding eigenvector. \( W=(W_1, W_2, \ldots, W_n) \), where \( W_i \) represents the relative weight value of the corresponding index in this criterion layer.
Figure 1. Risk assessment hierarchical model of lightning disaster in oil storage depots

Table 1. Scale method 1-9

| Scale   | Definition                                           |
|---------|------------------------------------------------------|
| aij=1   | Factor Ai is equally important to factor Aj          |
| aij =3  | Factor Ai is slightly more important than factor Aj  |
| aij =5  | Factor Ai is obviously more important than factor Aj |
| aij =7  | Factor Ai is strongly more important than factor Aj  |
| aij =9  | Factor Ai is extremely more important than factor Aj |
| aij =2, 4, 6, 8 | Between the intermediate value of Ai and Aj judgment |
| Reciprocal | aij =1/ aij                                      |
2.3. Consistency test
Since the consistency of the judgment matrix may be biased, it should be tested to ensure the rationality of the weight. This process should introduce three indicators, namely the consistency index, CI, the average random consistency index, RI, and the consistency ratio, CR [17]. The calculation steps are as follows:

1. Calculation of CI:

\[
CI = \frac{\lambda_{\text{max}} - n}{n - 1}
\]

2. Calculation of CR:

\[
CR = \frac{CI}{RI}
\]

RI selects the corresponding value in the average RI table (Table2) according to the order n of the judgment matrix.

| Table 2. Average random CI |
|---------------------------|
| Order of judgment matrix  | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
| RI                       | 0  | 0  | 0.52 | 0.89 | 1.12 | 1.26 | 1.36 |

When CR \(\leq 0.1\), the consistency of the judgment matrix meets the requirements or should be adjusted until it meets the consistency requirements [17].

2.4. The calculation of the comprehensive weight
The relative weight of the individual factors should be integrated to calculate the comprehensive weight of each during the entire risk assessment process. The calculation process of the comprehensive weight occurs from top to bottom, and it is assumed that the m factors of the second layer belong to the highest layer, that is, the weight of the first layer is:

\[
W^2 = [W^2_1, W^2_2, \ldots, W^2_m]^T
\]

In the third layer, the relative weights of the n factors belonging to a j factor in the second layer are as follows:

\[
k^3 = [k^3_1, k^3_2, \ldots, k^3_n]^T
\]

Then the comprehensive weight of these n factors of the third layer belonging to the highest level is as follows:

\[
W^3 = [k^3_1, k^3_2, \ldots, k^3_n]^T g W^2_j
\]

Therefore, a consistency test is required after calculating the comprehensive weight of each layer of factors. If the requirements are not met, they must be adjusted from the bottom until reaching an adequate level. Finally, all the factors are ranked according to the comprehensive weight.

3. Lightning disaster risk assessment of oil storage depots based on the fuzzy comprehensive analytic hierarchy process
The assessment of lightning disaster risk assessment of oil storage depots involves various factors that are difficult to quantify, such as the path of a thunderstorm and the topography. The fuzzy comprehensive analytic hierarchy process can resolve this problem, while the relevant theories pertaining to fuzzy mathematics can be used to quantify these qualitative factors.
3.1. Determining the index set of the evaluation system
The entire evaluation process was analyzed according to the lightning strike risk mechanism in storage tanks. The risk evaluation index, \( u \), was selected correctly and reasonably, in which \( U = \{ u_1, u_2, \ldots, u_n \} \). The evaluation indexes established in this paper are shown in Section 2.1.

3.2. Determining the risk level of the evaluation index
The risk level \( V \) of the evaluation index, in which \( V = \{ v_1, v_2, \ldots, v_k \} \) is essential for determining the membership degree of the index, is usually determined by combining relevant standards with relevant experts. The accuracy of the actual risk assessment is affected when the risk level \( k \) is small, while the indicators are difficult to quantify when the risk level \( k \) is too large. Therefore, levels 3-7 are usually employed in research. In this paper, the risk level \( K \) of 5 was selected, that is \( V = \{ v_1, v_2, \ldots, v_5 \} \), in which \( v_1 \) - safe, \( v_2 \) - relatively safe, \( v_3 \) - low risk, \( v_4 \) - medium risk, and \( v_5 \) - high risk.

3.3. Determining the weights of the rating indicators
Due to the interaction between the indicators and their individual influence on the evaluation results, it is necessary to determine the weight value of each indicator. For example, the weight of \( n \) indicators under indicator \( x \) is \( W_x = [ W_1, W_2, \ldots, W_n ]^T \).

3.4. Determining the membership degree of the evaluation index
Membership degree refers to a number between 0 and 1 that can be used to express the degree to which an element belongs to the fuzzy set. The membership degree of the evaluation index in this paper reflected the risk level corresponding to the risk index of the project in the actual situation. The primary methods currently used to determine the actual membership are shown in Table 3. In this paper, the trapezoidal distribution was selected as the membership function.

| Membership Functions | Rectangular Distribution | Trapezoidal Distribution |
|----------------------|--------------------------|--------------------------|
| Smaller              | \( A(x) = \begin{cases} 1 & x \leq a \\ 0 & x > a \end{cases} \) | \( A(x) = \begin{cases} 1 & x < a \\ x-a/b-a & a \leq x \leq b \\ 0 & x > b \end{cases} \) |
| Middle               | \( A(x) = \begin{cases} 1 & a \leq x \leq b \\ 0 & x < a \text{or} x > b \end{cases} \) | \( A(x) = \begin{cases} 1 & b \leq x < c \\ d-x/d-c & c \leq x < d \\ 0 & x \geq d \end{cases} \) |
| Bigger               | \( A(x) = \begin{cases} 1 & x \geq a \\ 0 & x < a \end{cases} \) | \( A(x) = \begin{cases} 0 & x < a \\ x-a/b-a & a \leq x \leq b \\ 1 & x > b \end{cases} \) |

(1) The membership degree calculation of the quantitative indicators considered the lightning strike density as an example. When assuming that the lightning strike density parameter of the project is 3.25 times/a•km\(^2\) from the field data, risk level should be determined according to the existing lightning strike density.
Table 4. Classification standard for lightning strike density

| Danger Level | Level I | Level II | Level III | Level IV | Level V |
|--------------|---------|----------|-----------|----------|---------|
| Lightning Strike Density (times/(a·km²)) | [0,1)  | [1,2)  | [2,3) | [3,4) | [4,∞) |

Here, v₁, v₂, v₃, v₄, and v₅ are the median values of levels I, II, III, IV, and V, respectively, and 0.5, 1.5, 2.5, 3.5, and 4.5, according to the membership function calculation formula of the small index:

\[
\lambda_{v_1}(v_j) = \frac{3.25 - 2.5}{3.5 - 2.5} = 0.75
\]

\[
\lambda_{v_2}(v_j) = \frac{3.5 - 3.25}{3.5 - 2.5} = 0.25
\]

The membership degree of the lightning stroke density is shown in Table 5.

Table 5. Membership degree of the lightning strike density

| Danger Level | Level I | Level II | Level III | Level IV | Level V |
|--------------|---------|----------|-----------|----------|---------|
| Lightning Strike Density | 0 | 0 | 0.75 | 0.25 | 0 |

(2) The qualitative indicators were directly determined by the acquisition of the field data. Considering the thunderstorm path as an example, and when assuming that the sum of the percentages of the maximum three moving directions of the thunderstorm is 42%, then the thunderstorm path belongs entirely to level II, as shown in Table 6.

Table 6 Thunderstorm path membership

| Risk Level | Level I | Level II | Level III | Level IV | Level V |
|------------|---------|----------|-----------|----------|---------|
| Thunderstorm Path | 0 | 1 | 0 | 0 | 0 |

3.5. Fuzzy comprehensive evaluation

Considering all the factors, the comprehensive evaluation of the system should start at the bottom index and proceed to the top, ultimately calculating the comprehensive evaluation results of the entire system. The specific steps were as follows:

First, its membership matrix was obtained according to the membership degree integration of the existing underlying indicators.

For example, the membership degrees of indicators D₁, D₂, and D₃ at the lower level of indicator C₅ that is subordinate to the five evaluation levels are:

\[
R_{D_1} = \begin{bmatrix} r_{D_{11}}, r_{D_{12}}, \ldots, r_{D_{15}} \end{bmatrix}
\]

\[
R_{D_2} = \begin{bmatrix} r_{D_{21}}, r_{D_{22}}, \ldots, r_{D_{25}} \end{bmatrix}
\]

\[
R_{D_3} = \begin{bmatrix} r_{D_{31}}, r_{D_{32}}, \ldots, r_{D_{35}} \end{bmatrix}
\]

According to the weight values of indicators D₁, D₂, and D₃, the fuzzy comprehensive evaluation results of indicator C₅ can then be calculated as:
where “•” represents the synthesis operator of the fuzzy matrix. The commonly used synthesis operators primarily include the main prominent factor type, the weighted average type, and the small upper bound type. In this paper, the $M(\wedge, \vee)$ operator of the main prominent factor type was adopted, in which $\wedge$ referred to the minimum value and $\vee$ denoted the maximum value. The formula can be expressed as:

$$a_j b_j = \frac{a_j}{\sum_{i=1}^{m} (a_i \wedge b_j)} \quad j = (1, 2, 3, \ldots, m)$$  \hspace{1cm} (12)$$

According to the calculation results, the fuzzy comprehensive evaluation result of index $C_5$, namely the membership degree, was:

$$R_{C_5} = [r_{C_5,1}, r_{C_5,2}, \ldots, r_{C_5,5}]$$  \hspace{1cm} (13)$$

Similarly, index $C_5$ belonged to the subordinate index of index $B_2$. To obtain the membership degree of index $B_2$, the membership degrees, $R_{B_1}$, $R_{B_2}$, and $R_{B_3}$ of indexes $C_5$, $C_6$, and $C_7$ were calculated and combined with the corresponding weight value $W_{B_2} = [w_{C_5}, w_{C_6}, w_{C_7}]$, while the $M(\wedge, \vee)$ operator was used to calculate the membership degree of index $B_2$:

$$R_{B_2} = W_{B_2} \cdot R_{B_2} = W_{B_2} \cdot \begin{bmatrix} R_{B_1} \\ R_{B_2} \\ R_{B_3} \end{bmatrix} = \begin{bmatrix} w_{C_5}, w_{C_6}, w_{C_7} \end{bmatrix} \cdot \begin{bmatrix} r_{C_5,1} & r_{C_5,2} & \ldots & r_{C_5,5} \\ r_{C_6,1} & r_{C_6,2} & \ldots & r_{C_6,5} \\ r_{C_7,1} & r_{C_7,2} & \ldots & r_{C_7,5} \end{bmatrix} = [r_{B_2,1}, r_{B_2,2}, \ldots, r_{B_2,5}]$$  \hspace{1cm} (14)$$

Finally, the membership degrees, $R_{B_1}$, $R_{B_2}$, $R_{B_3}$, and $R_{B_4}$ of indexes $B_1$, $B_2$, $B_3$, and $B_4$ were calculated and combined with the corresponding weight value $W_{A} = [w_{B_1}, w_{B_2}, w_{B_3}, w_{B_4}]$, while the $M(\wedge, \vee)$ operator was used to calculate the membership degree of target layer $A$:

$$R_{A} = W_{A} \cdot R_{A} = W_{A} \cdot \begin{bmatrix} R_{B_1} \\ R_{B_2} \\ R_{B_3} \\ R_{B_4} \end{bmatrix} = \begin{bmatrix} w_{B_1}, w_{B_2}, w_{B_3}, w_{B_4} \end{bmatrix} \cdot \begin{bmatrix} r_{B_1,1} & r_{B_1,2} & \ldots & r_{B_1,5} \\ r_{B_2,1} & r_{B_2,2} & \ldots & r_{B_2,5} \\ r_{B_3,1} & r_{B_3,2} & \ldots & r_{B_3,5} \\ r_{B_4,1} & r_{B_4,2} & \ldots & r_{B_4,5} \end{bmatrix} = [r_{A,1}, r_{A,2}, \ldots, r_{A,5}]$$  \hspace{1cm} (15)$$

The $r_1, r_2, r_3, r_4,$ and $r_5$ in $R_{A} = [r_1, r_2, \ldots, r_5]$ represent the membership degree between the evaluation item and the five evaluation levels, namely I, II, III, IV, and V. Although it is convenient and simple to use the principle of maximum membership degree to determine the risk level of the project, the information may be lost, while the accuracy of the evaluation results can be affected to some extent. Therefore, this paper adopted the weighted average method for optimization. For the convenience of calculation, the five evaluation levels, I, II, III, IV, and V, were quantified by 1, 3, 5, 7, and 9. The final evaluation formula is as follows:

$$S = r_1 + 3r_2 + 5r_3 + 7r_4 + 9r_5$$  \hspace{1cm} (16)$$
4. Classification of the risk levels of the index factors
The degree of membership is obtained by determining the risk level of each index, after which the composite weights of the calculated index factors are combined to assess the safety of the project. In this paper, the risk level of the indicators was divided into five levels according to Table 7.

Table 7. Risk assessment criteria for lightning disaster of oil storage depots

| Risk Level | Description | S∈[0, 10] |
|------------|-------------|-----------|
| Level I    | The comprehensive evaluation is expressed by S. The smaller the S value, the lower the lightning risk. The larger the S value, the higher the lightning risk. | S∈[0, 2), safety |
| Level II   | S∈[2, 4), relatively safety | |
| Level III  | S∈[4, 6), low risk | |
| Level IV   | S∈[6, 8), middle risk | |
| Level V    | S∈[8, 10), high risk | |

\[ S = r_1 + 3r_2 + 5r_3 + 7r_4 + 9r_5, \]
where \( r_1, r_2, r_3, r_4, \) and \( r_5 \) denote the final membership degrees of Levels I, II, III, IV, and V, which are assigned 1, 3, 5, 7, and 9 via the weighted average method.

5. Conclusion
This paper analyzes various factors that may cause lightning disaster in oil storage depots according to the complexity and high risk of the oil storage depots itself. Analysis of the lightning disaster mechanism of the storage tanks and the lightning risk system of typical buildings allows the risk level of the evaluation index to be divided according to the relevant lightning standards both domestically and abroad and the knowledge and experience of relevant experts. The fuzzy comprehensive analytic hierarchy process is selected to evaluate the lightning disaster risk of oil storage depots and to assess the lightning disaster risk of the entire oil storage facility to determine the risk level. It forms a complete lightning disaster risk assessment system for oil depots, providing a reference for creating lightning protection measures for oil storage depots. The specific results are as follows:

(1) A risk assessment index system is established for lightning disasters in oil storage depots, including four first-class assessment indexes, 13 second-class assessment indexes, and 13 third-class assessment indexes. This system intuitively expresses the subordinate relationship between various risks that may lead to lightning accidents in oil storage depots while introducing the acquisition method of each bottom risk index.

(2) The hierarchy model of lightning disaster risk assessment for oil storage depots is established. The analytic hierarchy process is used to determine the weight of each risk index and sort the importance degree. The fuzzy comprehensive analytic hierarchy process is then employed to assess the lightning disaster risk in oil storage depots to obtain the final risk level.

(3) The risk index of lightning disaster in oil storage depots is strictly classified according to the risk levels.

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References

[1] Liu X G. Common lightning disasters and protective measures in oil depot[J]. Brand and standardization, 2012(10): 48-49. https://doi.org/10.3969/j.issn.1674-4977.2012.10.039

[2] Necci A, Antonioni G, Bonvicini S, et al. Quantitative assessment of risk due to major accidents triggered by lightning[J]. Reliability Engineering & System Safety, 2016: S0951832016003539. https://doi.org/10.1016/j.ress.2016.05.009

[3] Necci A, Antonioni G, Cozzani V, et al. Assessment of lightning impact frequency for process equipment[J]. Reliability Engineering & System Safety, 2014, 130: 95-105. https://doi.org/10.1016/j.ress.2014.05.001

[4] Necci A, Argenti F, Landucci G, et al. Accident scenarios triggered by lightning strike on atmospheric storage tanks[J]. Reliability Engineering System Safety, 2014, 127(127): 30-46. https://doi.org/10.1016/j.ress.2014.02.005

[5] Necci A, Antonioni G, Cozzani V, et al. A model for process equipment damage probability assessment due to lightning[J]. Reliability Engineering & System Safety, 2013, 115: 91-99. https://doi.org/10.1016/j.ress.2013.02.018

[6] Renni E, Krausmann E, Cozzani V. Industrial accidents triggered by lightning[J]. Journal of Hazardous Materials, 2010, 184(1-3): 42-48. https://doi.org/10.1016/j.jhazmat.2010.07.118

[7] Borghetti A, Cozzani V, Mazzetti C, et al. Monte Carlo based lightning risk assessment in oil plant tank farms[C]. 2010 30th International Conference on Lightning Protection (ICLP). IEEE, 2010.

[8] Yu S Y, Ren Y, Qin B Q.. Research on risk assessment method of lightning disaster in Chongqing Based on Fuzzy Mathematics[J]. Disaster science, 2015(2): 75-78. https://doi.org/10.3969/j.issn.1000-811X.2015.02.014

[9] Wang S Y, Zou S Y, Wang L.. Comprehensive evaluation of lightning risk index in Dalian City Based on Fuzzy Mathematics[J]. Journal of Institute of disaster prevention, 2015, 17(4): 32-36. https://doi.org/10.1016/j.ijidp.2015.04.005

[10] Feng H, Li G L.. Research on the risk division of lightning disaster in Shijiazhuang based on Fuzzy Mathematics[J]. Research on agricultural disaster, 2013, 3(z1): 45-47. https://doi.org/CNKI:SUN:NZYJ.0.2013-Z1-020

[11] Gallego L E, Duarte O, Torres H, et al. Lightning risk assessment using fuzzy logic[J]. Journal of Electrostatics, 2004, 60(2-4): 233-239. https://doi.org/10.1016/j.elstat.2004.01.014

[12] Hu H B, Wang Y C, Xiong Y J. Risk assessment of lightning disaster in Beijing based on AHP model[J]. Journal of natural disasters, 2010, 19(1): 104-109. https://doi.org/CNKI:SUN:ZYZH.0.2010-01-017

[13] Yuan X L, Ji H, Cheng L. Risk zoning of lightning disaster in Hei long jiang Province Based on AHP model[C]. Annual meeting of China Meteorological Society Urban Meteorology, Make life better. 2010. https://doi.org/10.3969/j.issn.1004-9045.2010.03.013

[14] Zhu X R, Kang Q. Risk zoning of lightning disaster in Fang cheng gang area based on AHP[J]. Research on agricultural disaster, 2016, 6(4): 24-26. https://doi.org/CNKI:SUN:NZYJ.0.2016-04-010

[15] Li Y, Wang Y C, Liang J L. The application of fuzzy comprehensive evaluation method in the risk assessment of oil depot[J]. Petrochemical Technology, 2016(12). https://doi.org/10.3969/j.issn.1006-0235.2016.12.241

[16] Chen W, Sun L G, Ou L Z.. Research on regional lightning risk assessment method based on Fuzzy Analytic Hierarchy Process[J]. Modern agricultural science and technology, 2018(17)

[17] Saaty T L. Analytic Hierarchy Process[M]. Encyclopedia of Biostatistics. John Wiley & Sons, Ltd, 2005.