Ecological Vulnerability Evaluation Model of Sichuan-Tibet Railway Based on Fuzzy Matter-element Analysis

Fang Bao1,2, Jian Qiu1
1School Architecture and Design, Southwest Jiaotong University, Chengdu, Sichuan, 611756, China
2China Railway Eryuan Engineering Group CO.LTD, Chengdu, Sichuan, 610031, China
*Corresponding author’s e-mail: 190519720@qq.com

Abstract: In order to identify the ecological conditions of Sichuan-Tibet Railway, based on the vulnerability evaluation framework of “exposure-sensitivity-adaptation”, this paper selects 20 evaluation indexes including temperature, precipitation, snowfall, herb coverage, total number of plant species, population density and per capita GDP, and establishes a multi-element and multi-attribute comprehensive evaluation system. The comprehensive evaluation system is divided into eight basic judgment indexes, and the weight is determined based on the fuzzy matter-element analysis method. The basic judgment index scores are obtained through cluster analysis, and the ecological vulnerability evaluation model is established. It is expected to provide theoretical reference for the construction of Sichuan-Tibet Railway in ecologically fragile areas to protect and improve the ecological environment.

1. Introduction
Sichuan-Tibet Railway passes through the “ecological barrier of Qinghai-Tibet Plateau” in the national ecological security strategic pattern. The geographical environment along the railway is unique; the landform is complex; the ecosystem is diverse and the regional difference is obvious. It has four characteristics of engineering environment: “significant terrain height difference”, “strong plate activity”, “frequent mountain disasters” and “fragile ecological environment”. The railway crossing area is rich in biodiversity. It is a hot spot of diversity in China even in the whole world, with rich germplasm resources. It is also the main body of China’s five major forest regions - southwest mountain forest region, and an important distribution area of China’s three major natural grasslands - alpine meadow.

Ecological vulnerability refers to the sensitive response and self-recovery ability of the ecological environment when it is disturbed by external forces under specific regional conditions. It is an inherent attribute of the ecosystem with regionality and objectivity. It is the result of internal succession of the system, natural factors and human activities. According to the relevant research results at home and abroad, it is not difficult to find that vulnerability research has made rapid progress since the 21st century, which is characterized by diversification, multi-angle, refinement and integration, especially in the evaluation theoretical framework. Based on the framework of “exposure-sensitivity-adaptation”, this paper selects 20 comprehensive evaluation indexes including temperature, precipitation, snowfall, herb coverage, total plant species, population density and per capita GDP which can comprehensively demonstrate the vulnerability of the areas studied to establish a multi-factor and multi-attribute comprehensive evaluation system. However, in the traditional vulnerability evaluation research, the
weights of evaluation indexes are often assigned by analytic hierarchy process, expert scoring method and average weight method, which has strong subjectivity and great limitations. In this paper, fuzzy mathematics and matter-element analysis are organically combined, and an ecological vulnerability evaluation model based on fuzzy matter-element analysis is proposed and established, which emphasizes the internal relationship and interaction of the ecology along the Sichuan-Tibet Railway, and can effectively adapt to the multi-objective and multi-dimensional characteristics of the ecological vulnerability evaluation system along the Sichuan-Tibet Railway.

2. Adaptability of Fuzzy Matter-element Analysis
Existing results show that vulnerability research has made great progress in the diversification of evaluation data, horizontal spatial comparison, multi-angle analysis of vertical time sequence and multi-scale fine evaluation. However, the most critical step of index evaluation method is index weight assignment. At present, the methods used by scholars at home and abroad to select index weight are mainly analytic hierarchy process (AHP), expert scoring method and average weight method. Such methods have strong subjectivity and neglect the internal relationship of indexes.

Matter-element analysis is a science between mathematics and experiment, which was put forward by Chinese scholar Cai Wen in 1983. It uses the name of things \( N \), the characteristic \( C \), and the quantity value \( V \) about the characteristic to form a ternary ordered group, namely \( R = (N, C, V) \). This triplet is called matter element. Since things are always connected and interacted with each other, sometimes the classical Contort set cannot be used to determine the quantity value of things, and some things have fuzzy attributes. If a characteristic quantity value describing matter element is fuzzy, the ternary ordered group is actually composed of thing \( N \), characteristic \( C \) and quantity value \( V \) about fuzzy characteristics, which is called fuzzy matter element \( (N, C, V) \).

The vulnerability along Sichuan-Tibet Railway is the product of the nonlinear comprehensive action of various factors in the regional system under the natural and social economic environment, and it is a complex thing involving multiple factors. The influencing factors of vulnerability have certain fuzziness, and the attribute and mechanism of each factor are different. The traditional mathematical methods have certain limitations and inapplicability in the study of things with complex fuzzy attributes and multi-element nonlinear effect. Therefore, this paper selects the fuzzy matter-element evaluation method as the basic method of vulnerability evaluation, and establishes the fuzzy matter-element model.

3. Ecological Vulnerability Evaluation Model of Sichuan-Tibet Railway
The evaluation of ecological vulnerability along Sichuan-Tibet Railway is a research process to quantitatively describe the degree of vulnerability. Its purpose is to quantify the vulnerability and provide scientific basis for the ecological construction of Sichuan-Tibet Railway. The ecological vulnerability evaluation model established in this paper uses cluster analysis to calculate the scores of basic judgment indexes and fuzzy matter-element analysis to calculate the weights of basic judgment indexes. The model mainly includes the following four steps:

(1) To establish the evaluation index system and determine the basic judgment indexes; (2) to calculate the scores of the basic judgment indexes; (3) to determine the weights of the basic judgment indexes; (4) to comprehensively evaluate the vulnerability of the divisions along the railway route.

3.1 Vulnerability Evaluation Index System and Basic Indexes of Judgment under the Framework of “Exposure-Sensitivity-Adaptation”

3.1.1 Vulnerability Evaluation Index System under the Framework of “Exposure-Sensitivity-Adaptation”
Vulnerability is regarded as the result of multiple factors. In 1996, IPCC defined vulnerability as “the degree of damage to a vulnerable system, which depends on its exposure, sensitivity and adaptability”. In this definition, the exposure is the proximity of the system to the disaster; the sensitivity is the damage of the system under pressure; the adaptability is the state of the system under pressure and the recovery ability of the system after damage. This framework takes the human environment coupling system as
the analysis object, and includes the social and ecological dimensions. It highlights the analysis of the internal mechanism of vulnerability, and points out the correlation between the vulnerability of regional society and ecosystem (human and ecological environment). Based on the framework of “exposure-sensitivity-adaptation”, this paper will study the ecological vulnerability along the Sichuan-Tibet Railway.

The key of ecological vulnerability evaluation along Sichuan-Tibet Railway depends on whether the index system is reasonable, whether it can represent the characteristics of ecological vulnerability, and whether the data source is reliable. As the data of ecological vulnerability evaluation along Sichuan-Tibet Railway is influenced by multiple factors, this paper starts from the connotation of vulnerability, and constructs a vulnerability evaluation index system based on “exposure sensitivity adaptation”, as shown in Table 1.

Table 1 Vulnerability Evaluation Indexes

| Criterion Layer | Symbol | Index Layer (Unit) | Index Calculation | Relevance | Index Description |
|-----------------|--------|--------------------|-------------------|-----------|-------------------|
| Exposure        | C₁     | Annual Average Wind Speed (m/s) | Annual Average Wind Speed of Divisions | + | Wind speed is the main contributor to wind erosion. |
|                 | C₂     | Annual Maximum Wind Speed (m/s) | Annual Maximum Wind Speed of Divisions |
|                 | C₃     | Annual Average Precipitation (mm) | Annual Average Precipitation of Divisions | + | Precipitation may lead to debris flow, landslides and collapse. |
|                 | C₄     | Annual Maximum Precipitation (mm) | Annual Maximum Precipitation of Divisions |
|                 | C₅     | Annual Minimum Precipitation (mm) | Annual Minimum Precipitation of Divisions |
|                 | C₆     | Annual Maximum Snow Depth (mm) | Annual Maximum Snow Depth of Divisions |
|                 | C₇     | Annual Maximum Snow Pressure (0.1 g/cm²) | Annual Maximum Snow Pressure of Divisions | + | Snowfall may bring about frozen earth. |
|                 | C₈     | Annual Snowfall (mm) | Annual Snowfall of Divisions |
|                 | C₉     | Annual Average Temperature (℃) | Annual Average Temperature of Divisions | | Lower temperature would increase the probability of snow, thus triggering frozen earth. |
|                 | C₁₀    | Annual Maximum Temperature (℃) | Annual Maximum Temperature of Divisions |
|                 | C₁₁    | Annual Minimum Temperature (℃) | Annual Minimum Temperature of Divisions |
|                 | C₁₂    | Annual Average Pressure (hPa) | Annual Average Pressure of Divisions | | Atmospheric pressure is related to temperature. The lower the atmospheric pressure, the lower the temperature. |
|                 | C₁₃    | Annual Minimum Pressure (hPa) | Annual Minimum Pressure of Divisions |
|                 | C₁₄    | Annual Maximum Pressure (hPa) | Annual Maximum Pressure of Divisions |
|                 | C₁₅    | Average Elevation | Average Elevation of Divisions | | The higher the altitude, the lower the temperature. |
|                 | C₁₆    | Average Gradient | Average Gradient of Divisions | + | Regions with steep gradient are prone to collapse and debris flow. |
3.1.2 Basic Indexes of Judgment

As the number of exposure indexes is as high as 16, the indexes of exposure are divided into eight basic indexes: storm wind, rainstorm, blizzard, extreme temperature, extreme pressure, geological disaster, sensitivity and adaptability. (see Table 2)

| Secondary Index | Symbol | Influencing Factor (Unit) |
|-----------------|--------|---------------------------|
| Storm Wind      | C1     | Annual Average Wind Speed (m/ s) |
|                 | C2     | Annual Maximum Wind Speed (m/ s) |
|                 | C3     | Annual Average Precipitation (mm) |
|                 | C4     | Annual Maximum Precipitation (mm) |
|                 | C5     | Annual Minimum Precipitation (mm) |
|                 | C6     | Annual Maximum Snow Depth (mm) |
| Rainstorm       | C7     | Annual Maximum Snow Pressure (0.1 g/ cm2) |
|                 | C8     | Annual Snowfall (mm) |
|                 | C9     | Annual Average Temperature (°C) |
| Rainstorm       | C10    | Annual Maximum Temperature (°C) |
|                 | C11    | Annual Minimum Temperature (°C) |
|                 | C12    | Annual Average Pressure (hPa) |
| Blizzard        | C13    | Annual Minimum Pressure (hPa) |
|                 | C14    | Annual Maximum Pressure (hPa) |
|                 | C15    | Average Elevation |
|                 | C16    | Average Gradient |
| Geological Disasters | C17   | Diversity Index |
|                 | C18    | Herbage Coverage |
| Sensitivity     | C19    | Population Density (person/ km2) |
|                 | C20    | Per capita GDP (person/ yuan) |
|                 | C17    | Diversity Index |
3.2 Description of Symbols

| Symbol | Connotation |
|--------|-------------|
| 𝜑ᵢ | Score of the 𝑖th natural disaster |
| 𝛾 | Score of sensitivity |
| 𝜌 | Score of adaptation |
| 𝑠ⱼ | Disaster grade score of the division included in the category of Grade 𝑗 |
| 𝑝ⱼ | Weight of the division to the disaster grade score of Category 𝑗 |
| 𝛽ⱼ | Sensitivity grade score of the division included in the category of Grade 𝑗 |
| 𝜁ⱼ | Weight of the division to the sensitivity grade score of Category 𝑗 |
| 𝜏ⱼ | Adaptation grade score of the division included in the category of Grade 𝑗 |
| 𝜈ⱼ | Weight of the division to the adaptation grade score of Category 𝑗 |

3.3 Calculation of the Scores of Basic Judgment Indexes

Based on the framework of “exposure-sensitivity-adaptation”, this paper establishes a multi-element and multi-attribute comprehensive evaluation system. Firstly, the evaluation indexes are divided into three categories: exposure, sensitivity and adaptability. Since the eight basic judgment indexes are based on the 20 evaluation indexes shown in Table 1, the scores of the eight basic judgment indexes are not clear. The purpose of this section is to find a reasonable method to calculate the scores of basic judgment indexes.

For the six basic judgment indexes of exposure including storm wind, rainstorm, blizzard, extreme temperature, extreme pressure and geological disasters, the scoring method is as follows: firstly, cluster analysis is carried out according to the influencing factors of natural disasters along the railway route, and the relevant data of the cluster center is analyzed, and then the disaster grade score of each category is determined. After that, the distance from the divisions to all cluster centers is calculated, and the weights of the scores of natural disaster grade are determined. Finally, the weighted sum of the scores of natural disaster grade is calculated, i.e., the score of each natural disaster.

For the two basic judgment indexes of sensitivity and adaptability, the calculation methods of scoring are exactly the same. Here only the calculation method of the scoring of the basic judgment index of sensitivity is described. First, cluster analysis is carried out according to the influencing factors of sensitivity in the divisions along the railway route, and the relevant data of the cluster centers is analyzed to determine the sensitivity grade score of each category. Then, the distance from the divisions to all cluster centers is calculated to determine the weights of the scores of the sensitivity grade. Finally, the weighted sum of the score of the sensitivity grade calculated, i.e., the score of the basic evaluation index of sensitivity.

3.3.1 Principles of Cluster Analysis

As a very important data mining technology, clustering method is a method that divides the data set into several groups automatically according to the similarity measurement standard between samples, and makes the similarity between samples in the same group as high as possible, while the similarity between samples belonging to different groups as low as possible.

K-means algorithm is the most commonly used clustering algorithm, and the main idea is as follows. With the given number of clusters $k$ and $k$ initial class centers, each point is divided into the class represented by the nearest class center. After all the points are allocated, the center of the class is recalculated according to all the points in a class, and then the steps of allocating and updating the class center are iterated until the change of the class center is very small or reaches the specified number of iterations. The K-means algorithm is shown in Table 4
Table 4 K-means Clustering Algorithm

Input: sample set $D = \{x_1, x_2, \cdots, x_m\}$ ($x_i$ is the dimensional vector of $n$); number of clusters $k$.

Process: Step 1: randomly select $k$ samples from $D$ as the initial mean vector $(\mu_1, \mu_2, \cdots, \mu_k)$, to enable: $C_i = \Phi (1 \leq i \leq k)$; 
Step 2: Step 2a: calculate the distance between the sample $x_j (1 \leq j \leq m)$ and each mean vector $\mu_i (1 \leq i \leq k)$:
$$d_{ij} = \sum_{k=1}^{n} (x_{jk} - \mu_{ik})^2$$
Step 2b: the category marker of $x_j$ is determined according to the nearest mean vector: $\lambda_j = \arg \min_{i \in \{1, 2, \cdots, k\}} d_{ij}$;
Step 3: the sample $x_j$ is categorized accordingly: $C_{\lambda_j} = C_{\lambda_j} \cup \{x_j\}$;
Step 4: calculate the new mean vector: $\mu_i' = \frac{1}{|C_i|} \sum_{x_{ij} \in C_i} x$ ($i = 1, 2, \cdots, k$)
Step 5: update the new mean vector: if $\mu_i' \neq \mu_i$, the mean vector $\mu_i$ is updated as $\mu_i'$; otherwise the mean vector remains unchanged.
Step 6: When the latest mean vectors are not updated, the iteration ends.

Output: category division $C = \{C_1, C_2, \cdots, C_k\}$

3.3.2 Calculation of the Score of the Basic Judgment Indexes of Exposure

In order to calculate the comprehensive scores of the six basic judgment indexes, this paper uses cluster analysis to divide a specific natural disaster into grades and get the grade score. Then the weights of the grade score based on the distance are calculated, and finally the comprehensive score of the natural disaster is obtained.

The specific calculation idea is: the cluster analysis of the influencing factors of natural disasters is conducted to get $k$ categories; the values of the cluster center are analyzed to get the disaster grade of each category; the grade scores are calculated according to the disaster grade. In accordance with the distance between the divisions and all cluster centers, the weights of the score of each disaster grade can be calculated. In theory, the smaller the distance is, the closer the division is to the category, and the greater the weight is. The comprehensive evaluation scores of natural disasters can be obtained by calculating the weighted sum of the grade scores.

The implementation algorithm is shown in Table 5.

Table 5 Calculation Process of the Score of Basic Indexes of Judgment of Exposure

Input: the $i$th sample set of natural disasters $D_i = \{x_1, x_2, \cdots, x_{2i}\}$ ($x_j = (x_{j1}, x_{j2}, \cdots, x_{jn})^T$, $x_j$ indicates the value vector of the natural disaster indexes of the $j$th division; each element of $x_j$ is the value of the third-level index corresponding to natural disaster); number of clusters $k$.

Step 1: conduct a cluster analysis of $D_i$ to obtain the clustering results: $C = \{C_1, C_2, \cdots, C_k\}$;
Step 2: determine the grade of natural disasters; conduct a qualitative analysis of the values of each cluster center to get the natural disaster grade of each cluster category (the most vulnerable category level to natural disasters is graded as 1 and the least prone to natural disaster is graded as $k$);
Step 3: the grade score of natural disasters is calculated. The natural disaster grade score of the division included in the category of Grade $j$ ($j = 1, 2, \cdots, k$) is: $s_j = \frac{k-j+1}{k}$
Step 4: calculate the distance between the divisions and $k$ cluster centers $d_1, d_2, \cdots, d_k$.
Step 5: calculate the weights of the division to the disaster grade score of the $k$ category.
Step 5a: the smaller $d_j$ is, the closer the division is to the $j$ category; so the weight of the division to $j$ ($i = 1,2,\ldots,k$) categories is: $w_j = 1 - \frac{d_j}{\sum_{j=1}^{k} d_j}$

Step 5b: in order to ensure the sum of weights of the natural disaster grade of the divisions totals 1, normalization processing is required. The resultant weight of the division to the disaster grade of the $j$ ($j = 1,2,\ldots,k$) category is: $p_j = \frac{1-w_j}{k-1}$

Step 6: the comprehensive score of natural disasters is calculated: $\varphi_i = \sum_{j=1}^{k} p_j \cdot s_j$

Output: the comprehensive score of the $i$th natural disaster $\varphi_i$.

3.3.3 Calculation of Sensitivity and Adaptability Scores

The calculation methods of sensitivity index and adaptability index are exactly the same. Taking sensitivity index as an example. Firstly, the sensitivity grade of each division is determined based on cluster analysis, and then the weight of the score at each level is calculated according to the distance from the divisions to all cluster centers, and the sensitivity score can be obtained by weighted sum of grade evaluation. The specific algorithm is shown in Table 6.

| Table 6 Calculation of Sensitivity Score |
|-----------------------------------------|

Input: sample set $D_i = \{x_1, x_2, \ldots, x_{2n}\}$ ($x_j = (x_{j1}, x_{j2}, \ldots, x_{jn})^T$, $x_j$ indicates the value vector of the sensitivity indexes of the $j$th division; each element of $x_j$ is the value of the third-level index corresponding to sensitivity); number of clusters $k$;

Step 1: conduct a cluster analysis of $D_i$ to obtain the clustering results: $C = \{C_1, C_2, \ldots, C_k\}$;

Step 2: determine the grade of sensitivity; conduct a qualitative analysis of the values of each cluster center to get the sensitivity results of each cluster category (the most sensitive category is graded as 1 and the most insensitive category is graded as $k$);

Step 3: the grade score of sensitivity is calculated. The sensitivity grade score of the division included in the category of Grade $j$ ($j = 1,2,\ldots,k$) is: $\beta_j = \frac{k-j+1}{k}$

Step 4: calculate the distance between the divisions and $k$ cluster centers $d_1, d_2, \ldots, d_k$.

Step 5: calculate the weights of the division to the sensitivity grade score of the $k$ category.

Step 5a: the smaller $d_j$ is, the closer the division is to the $j$ category; so the weight of the division to $j$ ($j = 1,2,\ldots,k$) categories is: $w_j = 1 - \frac{d_j}{\sum_{j=1}^{k} d_j}$

Step 5b: in order to ensure the sum of weights of the sensitivity grade of the divisions totals 1, normalization processing is required. The resultant weight of the division to the sensitivity grade of the $j$ ($j = 1,2,\ldots,k$) category is: $\zeta_j = \frac{1-w_j}{k-1}$

Step 6: the comprehensive score of sensitivity is calculated: $\gamma = \sum_{j=1}^{k} \beta_j \cdot \zeta_j$

Output: score of sensitivity $\gamma$

Similarly, the adaptability score can be calculated $\rho$: $\rho = \sum_{j=1}^{k} \tau_j \cdot v_j$

3.4 Calculation of the Weights of Basic Judgment Indexes

In 4.2, the scores of eight indexes are obtained. In order to calculate the weights of the scores, this paper proposes a weight calculation method based on fuzzy matter-element analysis. The steps of fuzzy matter-element analysis are as follows$^{14}$ $^{[12]}$:

Matter-element Establishment of Decision Scheme
For a multi-objective decision-making scheme, the things, characteristics and values of the scheme are described by ordered triples, that is, the thing is the scheme \( M_i \) \((i = 1, 2, \cdots, m)\), and there are \( m \) schemes in total; the characteristics are evaluation indexes \( C_i \) \((i = 1, 2, \cdots, n)\), and there are \( n \) evaluation indexes in total; the quantity value is the given value \( x_{ij} \), which represents the \( i \) evaluation index value of the \( i \) scheme \( M_i \), thus forming the following matter element, i.e., \( R = [\begin{array}{ccc}  x_{11} & x_{12} & \cdots & x_{1m}  \\  x_{21} & x_{22} & \cdots & x_{2m}  \\  \vdots & \vdots & \ddots & \vdots  \\  x_{n1} & x_{n2} & \cdots & x_{nm} \end{array}] \)

\[ R = [r_1, r_2, \cdots, r_m], \quad r_i (i = 1, 2, \cdots, m) \text{ represents the vector quantity of the evaluation index of } n \text{ of the } i \text{ scheme } M_i. \]

(1) Degree of Membership

In order to make multi-objective decision, the measurement standard should be determined. This standard is usually measured by degree of membership, which is usually determined by the following two methods.

For the larger and better decision:

\[ U_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \]  

For the smaller and better decision:

\[ U_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \]

max \( x_{ij} \) and min \( x_{ij} \) denote the maximum and minimum value of the corresponding value \( x_{ij} \) of each index in the multi-objective decision-making scheme.

In addition, the degree of membership can also be determined in the form of vector norm. Before introducing vector norm, the vector norm is first defined as follows:

**Definition 1:** if \( V(F) \) is a linear space over the number field \( F \), the real-valued function \( ||\cdot||: V(F) \rightarrow R \), if:

- Positive definiteness: \( ||x|| \geq 0 \), if and only if \( x=0 \), the equal sign holds;

- Homogeneity: \( ||kx|| = k \||x||, \quad k \in R; \)

- Triangle inequality: \( \|x + y\| \leq \|x\| + \|y\|; \)

Then the real-valued function \( ||\cdot|| \) is called the norm on \( V(F) \).

If \( x \) is a dimentional vector \( n, \ x = (x_1, x_2, \cdots, x_n)^T \), then the norm \( \infty - \) is defined as: \( \|x\|_\infty = \max(|x_1|, |x_2|, \cdots, |x_n|) \).

To sum up, the expression of degree of membership calculated by vector norm is shown as follows:

For the larger and better decision: \( U_{ij} = \frac{\|r_i\|_\infty - x_{ij}}{\max(x_{ij} - \min x_{ij})} \)  

For the smaller and better decision: \( U_{ij} = \frac{x_{ij} - \min x_{ij}}{\max(x_{ij} - \min x_{ij})} \)

(2) Transformation from Degree of Membership to Correlation Number

Correlation transformation is the transformation between degree of membership and correlation coefficient. Since the correlation coefficient is equivalent to the membership degree function, so the correlation coefficient \( \xi_{ij} \) can be determined by the coefficient of degree of membership \( U_{ij} \), which is \( \xi_{ij} = U_{ij} \quad (i = 1, 2, \cdots, n; j = 1, 2, \cdots, n) \)

(3) Establishment of Fuzzy Matter Element

Through the transformation from degree of membership to correlation coefficient, the value of membership degree can be used to replace the value of correlation coefficient. Based on this, the composite fuzzy matter element with correlation coefficient is established, which is formulated as: \( S = \)
Determination of Multi-objective Decision-making Scheme by Calculation and Analysis of Correlation Degree

The correlation degree is the degree of the correlation among various decision schemes. By calculating and sequencing, the final decision of the multi-objective decision scheme can be achieved. \( k_f \) denotes correlation degree. In this case, all the correlation degrees are combined to form a composite fuzzy matter element of correlation degree, which is represented by \( R_k \). If dealt with by the operator \( M(\cdot, \Theta) \), then:

\[
R_k = R_w \cdot S \quad (7)
\]

\[
R_k = \min \left(1, \sum_{j=1}^{n} R_{w_j} S_{jk} \right) \quad (8)
\]

\( R_w \) is the weighted composite matter element of each decision scheme index. If \( W_i \) is used to represent the weight of the \( i \)th evaluation index of each decision scheme, then:

\[
W_i = \frac{\sum_{j=1}^{n} \xi_{ji}}{\sum_{j=1}^{n} \sum_{i=1}^{m} \xi_{ji}} \quad (9)
\]

\[
R_w = (W_1, W_2, \ldots, W_n) \quad (10)
\]

By substituting \( R_w \) and \( S \) into equation (8), the correlation degree of each scheme can be obtained, and by sequencing the correlation degree values, the ranking results of each scheme can be obtained.

3.5 Vulnerability Scoring and Ranking

In this problem, the value of correlation degree is the vulnerability score of each division. The ranking of vulnerability of each division can be obtained by sorting the degree of correlation.

4. Conclusion

Based on the framework of “exposure-sensitivity-adaptation”, this paper selects 20 evaluation indexes including precipitation, temperature, snowfall, population density and per capita GDP, and establishes a multi-element and multi-attribute comprehensive evaluation model of Sichuan-Tibet Railway based on 8 basic judgment indexes. The model is mainly composed of three parts: first, based on the cluster analysis, the score of eight basic judgment indexes of each division is obtained; second, the multi-objective decision-making scheme is realized by using fuzzy matter-element analysis and calculating the correlation degree; third, the rationality of the evaluation is tested by introducing the methods of separation degree, degree of aggregation, classification matrix and matrix norm. Based on this, the vulnerability of ecosystem can be evaluated. In the next stage, the author will take the Yachang section of Sichuan-Tibet Railway as the research object to apply and verify the vulnerability assessment model proposed in this paper. The evaluation results can provide theoretical guidance for targeted ecological environment protection and improvement of Sichuan-Tibet Railway construction.

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