Post-Project Analysis Modeling of Environmental Impacts of Coal Mining Based on Structural Entropy Weight-Fuzzy Comprehensive Evaluation

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Abstract: A significant move in the implementation of the ecological civilization construction is to establish a complete post-project analysis model and give full play to its function in environmental management. Starting from the index system established under the PSR framework and the comprehensive assessment method, a post-project analysis (PPA) model was constructed for the environmental impacts of coal mining based on the structural entropy weight-fuzzy comprehensive evaluation, the structural entropy weight method and judging principle of effectiveness of the maximum membership degree were introduced into the model, so that the comprehensive assessment results were reasonable. Through an example analysis, the assessment results basically coincided with the reality, thus verifying the effectiveness of the assessment model.

1. Introduction
The sustainable development of coal resources has given rise to a series of resource and environmental problems such as land subsidence, destruction of water resources and disturbance of the earth’s surface, which have gradually become the major problems restricting the sustainable economic and social development in China. With the implementation of three major national strategies—“the Belt & Road” construction [1], Beijing-Tianjin-Hebei coordinated development and development of Yangtze River Economic Belt, China has taken the clean and high-efficient development and utilization of coal as the foothold and top priority of transformation and development of energy sources, energetically resolved the surplus production capacity, and provided advantageous conditions for the coal industry to transform the development mode, promoting the supply-side structural reform and optimizing the layout and structure. Strengthening the sustainable and effective protection and management of coal resource development environment, containing the ecological deterioration trend [2], and practically improving the quality of human settlement will be of great significance for facilitating the healthy development of national economy and society.

As an effective means of environmental management, the environmental impact assessment system plays a significant role in the determination of the economic development direction, prevention of the environmental pollution and ecological damage, and other major decisions. The theory and practice of environmental impact assessment have experienced the long-term development history in China, a relatively complete environmental assessment management system has been formed, which has promoted the coordinated development of construction activity and environmental protection. However, the post-project analysis (PPA) of sustainable environmental impacts has not been systematically and
effectively managed, yet, which is to the disadvantage of the whole-process assessment and supervision of project environmental impacts.

2. Domestic (China) and Foreign Research Progress
The foreign research on the post-project analysis (PPA) was started in the 1980s [3]. In 1988, through a comparative analysis of 11 case studies, the Economic Commission for Europe (ECE) determined the environmental impact assessment methods used in the projects which were successful in the PPA so that the other projects could improve their environmental impact assessment methods in practice, and meanwhile, ECE proposed the usage of PPA and the relationship between PPA and environmental impact assessment, and confirmed the classification and implementation procedures of PPA, etc. [4]. In 1996, Mellinger et al. put forward the job contents of PPA, including two parts: retrospective environmental impact assessment and post-project environmental impact assessment. Isaac Kow Tetteh [5] et al. conducted the PPA of three coastal communities around Kumasi Dam in Ghana 30 years after it was completed and put into use, used the network diagram containing a mathematical model in the impact recognition and analysis, and expressed the expected environmental impacts with the quantitatively weighted impact score, and the results showed that the dam generated obvious adverse effects on the environmental quality of communities; Branis et al. raised a PPA method integrating the qualitative analysis and quantitative analysis, and verified the accuracy of environmental impact prediction by comparing the actual environmental impacts with the expected environmental impacts, with a coal mine in Ohio, America, taken for example. A. K. Chondhary [6] et al. from Loughborough University, UK, studied the effects of PPA text on the problem handling, management strengthening, etc. of organizations.

The PPA-related research in China was started in the 1990s. This concept proposed derived from some problems in the execution and implementation of environmental impact assessment system, which influenced the deep implementation of environmental impact assessment and its actual results and effects, and it was deemed that post evaluation was a verification and supplementation of original evaluation [23]; in 1995, Bian G G and Wang H D et al. analyzed the problems existing in the then environmental impact assessment, including the poor operability and low prediction quality, put forward that the PPA work of significant polluting projects should be a supplementary means of environmental impact assessment management, and expounded the PPA objects, contents, working procedures, evaluation precision, feasibility verification and feasibility report compilation principles [8]; in 1998, Yang C W discussed about the problems existing in the then environmental impact assessment, and expounded the necessity of post-project (retrospective) analysis of environmental impacts [9]. In 1999, Wang G C and Huang X S et al. stated that the PPA was an important means of improving the effectiveness of environmental impact assessment, and taking PPA work of Longhai Jiaomei Industrial Comprehensive Development Zone in Fujian Province for example, expounded the main contents and technical route of PPA in this development zone [10]; in 2001, Dong X L and Zhao J Q et al. elaborated the importance and necessity of PPA system of highway construction projects, positioned the PPA work at the information feedbacks like assessment of project operation phase and implementation efficiency of project decisions, and discussed about the functions, organization and working procedures of PPA system [11]; in 2007, Cai W X et al. discussed about the concept, classification, applicable objects, significance and contents of PPA, and proposed its management and implementation procedures [12]. In 2009, the scholar Zhang S L theoretically studied and practiced the PPA work of coal field development, with the main contents of PPA framework, post evaluation contents and technical method system, and carried out the post evaluation by taking Yimin Open Pit Mine, Heidaigou Open Pit Mine and Shengli No.1 Open Pit Mine for examples [13]; in 2010, Cai Z L and Hu G R et al. systematically studied the main contents of PPA work of coal mining, and then by taking the PPA work of Jinbaotou Coal Mine for example, obtained the conclusion that the special post evaluation work of surface subsidence and underground water in mining area or working face should be carried out [14]; in 2013, Liu W R and Mai F D et al. corrected the related parameters in the price assessment of ecosystem service functions, implemented the cost-benefit analysis of accumulative ecological impacts of Pansan coal mining over the 20 years, and explored the quantitative analysis and application of ecological benefits and costs in
the PPA work of coal mining project \cite{15}; in 2014, Chen K Q, Wang D S, Mai F D and Shen Y et al. studied the PPA technical method system of reservoir project, coal mining project and highway project \cite{16}; in 2015, Zhang C J established a “three-nature” post evaluation model for Tashan Coal Mine, and conducted a comprehensive technical evaluation of Tashan Coal Mine using the fuzzy comprehensive evaluation method based on the expert scoring method \cite{17}; in 2016, Lian Z L discussed about the formulation of PPA standard, situation, working procedures and evaluation process of marine petroleum development project \cite{18}; in 2019, after analyzing the eco-environmental impact characteristics of an open pit coal mine in dry steppe region, Qin H Z came up with the features and emphases of PPA work of the regional eco-environmental impacts. Taking No.1 Open Pit Coal Mine in Shengli mining area for example, they used the retrospective analysis method, GeoEye remote-sensing image and QuickBird remote-sensing digital image interpretation to carry out the eco-environmental impact post evaluation from the angles of land utilization, vegetation coverage and water and soil erosion \cite{19}; in 2020, Xu X C et al. expounded the construction process of eco-environmental impact post evaluation system of water conservancy project, with the emphasis laid on analyzing the composition of evaluation index system \cite{20}.

Foreign PPA-related researches have mainly concentrated on the evaluation contents and methods, while domestic ones have laid the particular emphasis on the theory and technology of post evaluation, including post evaluation technical method, management system, etc. However, the post evaluation index system establishment and comprehensive evaluation model have been scarcely explored.

Based on a summary of the existing research results, a coal mining post evaluation model based on structural entropy weight-fuzzy comprehensive evaluation was proposed. A set of reasonable coal post evaluation index system was constructed under the PSR framework. The structural entropy weight method was used to assign weights to this index system, effectively avoiding the subjectivity of weight assignment. Next, the improved fuzzy comprehensive evaluation method was adopted to comprehensively judge the index system, and the effectiveness of the maximum membership of fuzzy comprehensive evaluation was verified and improved.

3 Construction of Structural Entropy Weight-Fuzzy Comprehensive Evaluation Model

3.1 Coal mining post evaluation index system based on PSR framework

The press-state-response (abbreviated as PSR) was proposed by a Canadian statistician in the 1970s, and index systems of economic budgets and environmental problems are established based on the PSR framework.

The PSR model was taken as the conceptual model of index system, the content scope of each index was defined, and the post evaluation index system of coal mining was divided into target layer, project layer, factor layer and index layer.

The target layer aims to evaluate the implementation effect of coal environmental protection and pollution prevention work; the project layer includes three indexes: press, state and response; the factor layer presents the concrete design contents of project layer, and the press indexes include resource consumption, pollutant discharge (water pollutant discharge, air pollutant emission, noise emission and solid waste discharge) and eco-environmental impact; the state indexes include economic benefit, environmental benefit and social effect; the response indexes include response of laws and regulations, response of governance effect, response of fund utilization and response of environmental management effect.

| Target layer | Project layer | Factors layer | Index layer |
|--------------|--------------|---------------|-------------|
| Post-evaluation index | Pressure indicators | Resource consumption U1 | The intensity of water consumption U_{11} |
|               |              | Energy intensity U_{12} | |
|               |              | Water pollution | SS discharge intensity of mine water U_{21} |
| System                                                                 | Discharge $U_2$                                                                 | COD discharge intensity of mine water $U_{22}$ |
|-----------------------------------------------------------------------|---------------------------------------------------------------------------------|-----------------------------------------------|
|                                                                       | Mine drainage intensity per unit product $U_{23}$                               |                                               |
|                                                                       | Domestic sewage SS discharge intensity $U_{24}$                                |                                               |
|                                                                       | Domestic sewage COD discharge intensity $U_{25}$                                |                                               |
|                                                                       | Domestic sewage BOD5 discharge intensity $U_{26}$                                |                                               |
|                                                                       | Discharge intensity of ammonia nitrogen in domestic sewage $U_{27}$             |                                               |
|                                                                       | Domestic sewage discharge intensity per unit product $U_{28}$                   |                                               |
| Emission of air pollution $U_5$                                        | $SO_2$ emission intensity $U_{31}$                                              |                                               |
|                                                                       | Dust emission intensity $U_{32}$                                                |                                               |
|                                                                       | Unorganized dust emission intensity $U_{33}$                                    |                                               |
|                                                                       | Discharge intensity per unit product $U_{34}$                                   |                                               |
|                                                                       | Night noise emission intensity $U_{34}$                                         |                                               |
| Noise emissions                                                        | Daytime noise emission intensity $U_{43}$                                       |                                               |
|                                                                       | Night noise emission intensity $U_{44}$                                         |                                               |
| Solid waste discharge $U_5$                                            | Discharge intensity of general industrial solid waste $U_{51}$                |                                               |
|                                                                       | Discharge intensity of hazardous waste $U_{52}$                                |                                               |
| Ecological and environmental impact $U_6$                             | Soil compliance rate $U_{61}$                                                   |                                               |
|                                                                       | Settlement rate of ten thousand tons $U_{62}$                                  |                                               |
|                                                                       | Covers an area of strength $U_{63}$                                            |                                               |
|                                                                       | Vegetation cover ratio $U_{64}$                                                 |                                               |
|                                                                       | Groundwater level decline intensity $U_{65}$                                    |                                               |
| Economic benefits $U_7$                                                | Investment in environmental protection as a percentage of GDP $U_{71}$          |                                               |
|                                                                       | Process cost expense ratio $U_{72}$                                             |                                               |
| Environmental benefits $U_4$                                          | Emission pollutant concentration $U_{41}$                                      |                                               |
|                                                                       | Comprehensive water quality index of the region $U_{42}$                       |                                               |
|                                                                       | Regional atmospheric composite index $U_{43}$                                   |                                               |
| Social benefits $U_9$                                                  | Stakeholder Satisfaction $U_{91}$                                              |                                               |
|                                                                       | Changes in residents' quality of life $U_{92}$                                  |                                               |
|                                                                       | Number of pollution accidents $U_{93}$                                         |                                               |
| Legal and regulatory response $U_{10}$                                 | Implementation of environmental impact assessment $U_{10.1}$                   |                                               |
|                                                                       | Simultaneous execution $U_{10.2}$                                              |                                               |
|                                                                       | Completion of total volume control $U_{10.3}$                                  |                                               |
|                                                                       | Implementation of emission reduction tasks $U_{10.4}$                          |                                               |
| Response to governance effect $U_{11}$                                 | Domestic sewage pollutant discharge rate up to the standard $U_{11.1}$         |                                               |
|                                                                       | Mine drainage pollutant discharge rate up to the standard $U_{11.2}$           |                                               |
|                                                                       | The emission rate of air pollutants meeting the standards $U_{11.3}$           |                                               |
|                                                                       | Comprehensive utilization rate of gangue $U_{11.4}$                            |                                               |
|                                                                       | Noise emission rate $U_{11.5}$                                                 |                                               |
|                                                                       | Settlement remediation rate $U_{11.6}$                                         |                                               |
|                                                                       | Comprehensive utilization rate of mine water $U_{11.7}$                        |                                               |
|                                                                       | Comprehensive utilization rate of domestic sewage $U_{11.8}$                   |                                               |
| Fund utilization efficiency $U_{12}$                                   | Expenses for environmental pollution control $U_{12.1}$                        |                                               |
|                                                                       | Investment in environmental protection projects $U_{12.2}$                    |                                               |
|                                                                       | Investment rate of environmental technology innovation $U_{12.3}$              |                                               |
| Environmental management effectiveness response $U_{13}$             | Environmental Organization Setup $U_{13.1}$                                   |                                               |
|                                                                       | The emergency response plan $U_{13.2}$                                        |                                               |
|                                                                       | Employee environmental education and training investment rate $U_{13.3}$        |                                               |
|                                                                       | Implementation of the pollutant discharge permit system $U_{13.4}$             |                                               |
|                                                                       | Environmental tax payment $U_{13.5}$                                           |                                               |

### 3.2 Structural entropy weight method

The structural entropy weight method \cite{21} has the following basic thought: The system indexes and their internal interactions are analyzed, they are then decomposed into several independent hierarchical structures, the “typical ranking” of the indexes in the importance degree is formed by combining the Delphi experts investigation method and fuzzy analytical method, the uncertainties of “typical ranking” structure are quantitatively analyzed based on the entropy theory, followed by the calculation of entropy value and “blindness” analysis, the potential deviation data is calculated and processed, the relative importance ranking of indexes at the same layer is obtained, and the importance value of similar indexes at each layer is determined, namely, the index weight.
(1) Collect expert opinions and form “typical ranking”

The corresponding Delphi expert investigation form was designed according to the index system, the expert opinions in the related fields were collected and ranked, thus forming a “typical ranking” of the index system. The Delphi design table for the importance degrees of evaluation indexes are listed in Table 2.

| The index type | Assessor serial | The first | The second | … | N choose |
|----------------|-----------------|----------|-----------|---|----------|
| Index 1        |                 |          |           |   |          |
| 1              |                 | ✓        |           |   |          |
| 2              |                 | ✓        |           |   |          |
| 3              |                 |          | ✓        |   |          |
| …              |                 |          |           |   |          |
| m              |                 |          |           |   | ✓        |
| Index 2        |                 |          |           |   | ✓        |
| 1              |                 |          |           |   |           |
| 2              |                 |          |           |   | ✓        |
| 3              |                 |          |           |   |           |
| …              |                 |          |           |   |          |
| m              |                 |          |           |   | ✓        |
| Index n        |                 |          |           |   | ✓        |
| 1              |                 |          |           |   |           |
| 2              |                 |          |           |   |           |
| 3              |                 |          |           |   |           |
| …              |                 |          |           |   |          |
| m              |                 |          |           |   | ✓        |

(2) Blindness analysis of “typical ranking”

Step 1: Organize the expert opinions and form a ranking matrix, \( A(\mathbf{A} = (a_{ij})_{m \times n}, i = 1, 2, \ldots, m; j = 1, 2, \ldots, n) \) represents the evaluation given by the expert \( i \) to the index \( j \).

Step 2: Construct a membership function. The membership of ranking number \( a_{ij} \) is \( b_{ij} = \mu(a_{ij}) = \ln(m-a_{ij}) / \ln(m-1) \), \( m \) is the number of transformed parameters, taken as \( m=n+2 \), and a membership matrix \( B = (b_{ij})_{m \times n} \) is formed.

Step 3: Assume that the \( m \) experts have the same right of speech for the index \( j \), namely, the consensus reached by the \( m \) experts over the index \( j \) is calculated, and it is called the average recognition level \( b_j = (b_{1j} + b_{2j} + \ldots + b_{mj}) / m \).

The uncertainty generated by the recognition of expert \( i \) for index \( j \) is defined as the blindness of recognition and denoted as \( Q_j \), and \( Q_j = |\{\max(b_{1j}, b_{2j}, \ldots, b_{mj}) - b_j\} + |\min(b_{1j}, b_{2j}, \ldots, b_{mj}) - b_j|\} / 2| \).

Step 4: Determine the evaluation vector of index. The general recognition degree of \( m \) experts for each index \( i \) is expressed by \( x_i = b_i * (1 - Q_i) \), and the evaluation vector of \( m \) experts for the index \( j \) can be acquired through \( x_j \) as \( X = (x_1, x_2, \ldots, x_n) \).

(3) Normalization processing

The evaluation vector \( X \) is normalized, and \( w_j = x_j / \sum_{j=1}^{n} x_j \). The weight vector \( W = (w_1, w_2, \ldots, w_n) \) can be obtained.

3.3 Fuzzy comprehensive evaluation method

(1) Determine the index set of evaluation object

The evaluation object is evaluated. If there are \( n \) factors at the evaluation index layer, denoted as
(1) Determine the comment set of evaluation object

According to the evaluation criteria, the comments are divided into k classes \(v_1, v_2, v_3, \ldots, v_k\), thus forming a finite set of comments, that is, \(V = (v_1, v_2, v_3, \ldots, v_k)\).

(2) Determine the membership of evaluation object

After the index set of evaluation object is established, each evaluation index factor \(u_i\) is independently evaluated, the membership of factor \(u_i\) to the comment \(v_j\) is obtained, and thus a membership matrix of single factor \(u_i\) to the comment \(v_j\) is acquired as follows:

\[
R = \begin{bmatrix}
r_{11} & r_{12} & r_{13} & \cdots & r_{1k} \\
r_{21} & r_{22} & r_{23} & \cdots & r_{2k} \\
r_{31} & r_{32} & r_{33} & \cdots & r_{3k} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
r_{n1} & r_{n2} & r_{n3} & \cdots & r_{nk}
\end{bmatrix}
\]

Where for any \(i\), \(r_{i1} + r_{i2} + r_{i3} + \cdots + r_{ik} = 1\) holds true.

(3) Determine the weight of each evaluation index

The index weight is determined through the structural entropy weight method:

\[
W = (w_1, w_2, w_3, \ldots, w_n)
\]

(4) Fuzzy comprehensive evaluation

The fuzzy comprehensive evaluation is implemented through the compound operation, so as to obtain the evaluation result \(Z = W \ast R\):

(5) Judge the effectiveness of the maximum membership

Step 1: According to the fuzzy comprehensive evaluation matrix, calculate the effectiveness \(\alpha\) of the maximum membership principle:

\[
\alpha = \frac{k\beta - 1}{2\gamma(k-1)}
\]

Where \(\beta\) is the maximum membership of matrix, and \(\gamma\) is the secondary membership.

The effectiveness \(\alpha\) of fuzzy comprehensive evaluation matrix is calculated and judged according to the following criteria [23]. When \(0.5 \leq \alpha < 1\), the maximum membership principle is relatively effective, it is of low effectiveness under \(0 \leq \alpha < 0.5\), and totally becomes ineffectively under \(\alpha = 0\).

Step 2: If \(\alpha \geq 0.5\), the fuzzy comprehensive evaluation is conducted using the maximum membership principle, and if \(\alpha < 0.5\), the confidence criterion will be preferred.

Confidence criterion [24]: If the evaluation set \(\{V_1, V_2, \ldots, V_k\}\) is an ordered evaluation set, \(\lambda\) is the confidence, the membership of \(x\) to \(V_i\) is \(\mu_x(V_i)\), satisfying \(\sum_{i=1}^{k} \mu_x(V_i) = 1\). The evaluation object \(x\) belongs to the category \(V_{t_0}\), and then the following expressions hold:

\[
t_0 = \begin{cases}
\min\left\{t: \sum_{i=1}^{t} h_x(V_i) \geq \lambda, 1 \leq t \leq k\right\} & V_1 > V_2 > \cdots > V_k \\
\max\left\{t: \sum_{i=1}^{t} h_x(V_i) \geq \lambda, 1 \leq t \leq k\right\} & V_1 < V_2 < \cdots < V_k
\end{cases}
\]

According to the confidence criterion from the angle of “strong”, the “stronger”, the better, and the “strong” should account for a considerable proportion. The value range of confidence is generally 0.6-0.8, taken as 0.7 in this study.

The technical route of comprehensive evaluation model is shown in Figure 1.
The index system is constructed based on PSR framework. Determination of index weight involves collecting expert opinions and forming a "typical ranking." Using entropy theory, the blinding analysis of typical sorts is carried out. Determining the membership function, constructing the membership matrix, and calculating the average recognition are key steps. The degree of knowledge blindness is defined, and the overall awareness is obtained. The evaluation vector is calculated, and the weight vector is determined.

Figure 1: Technical Roadmap of Comprehensive Evaluation Model

4. Application Case Study
The proposed PPA model and method were verified by taking the PPA work of a coal mining enterprise in Shaanxi Province for example. The evaluation index system constructed by this enterprise is shown in Table 1.

(1) Calculation of index weight
A total of 30 experts in the coal mining industry and environmental protection field were selected to calculate the index weights, they were divided into three groups (10 in each group), the 51 indexes of the evaluation index system were investigated through the expert questionnaires, followed by the typical ranking of collected expert opinions and analysis of statistical results, and the weight coefficient results are seen in Table 3.
### Table 3: Calculation of Weight and Membership of Evaluation Indexes after Coal Mining

| Target layer | Project layer | Factors layer (weight) | Index layer (weight) | Survey data statistics |
|--------------|---------------|------------------------|---------------------|-----------------------|
|              |               |                       |                     | excellent  | good  | medium | general  | poor  |
|              |               | The intensity of water consumption U11 (0.472) | | 0.319 | 0.467 | 0.213 | 0.001 | 0|
|              |               | Energy intensity U12 (0.528) | | 0.412 | 0.394 | 0.103 | 0.091 | 0|
|              |               | SS discharge intensity of mine water U21 (0.128) | | 0.219 | 0.352 | 0.229 | 0.101 | 0.099 |
|              |               | COD discharge intensity of mine water U22 (0.106) | | 0.301 | 0.271 | 0.228 | 0.184 | 0.016 |
|              |               | Mine drainage intensity per unit product U23 (0.156) | | 0.252 | 0.308 | 0.331 | 0.101 | 0.008 |
|              |               | Domestic sewage SS discharge intensity U31 (0.154) | | 0.221 | 0.257 | 0.231 | 0.217 | 0.074 |
|              |               | Domestic sewage COD discharge intensity U32 (0.105) | | 0.321 | 0.357 | 0.214 | 0.102 | 0.006 |
|              |               | Domestic sewage BOD5 discharge intensity U33 (0.113) | | 0.174 | 0.406 | 0.301 | 0.097 | 0.022 |
|              |               | Discharge intensity of ammonia nitrogen in domestic sewage U34 (0.103) | | 0.194 | 0.327 | 0.227 | 0.186 | 0.066 |
|              |               | Domestic sewage discharge intensity per unit product U35 (0.135) | | 0.291 | 0.386 | 0.207 | 0.104 | 0.012 |
|              |               | SO2 emission intensity U41 (0.186) | | 0.294 | 0.461 | 0.102 | 0.136 | 0.007 |
|              |               | Dust emission intensity U42 (0.269) | | 0.217 | 0.354 | 0.278 | 0.137 | 0.014 |
|              |               | Unorganized dust emission intensity U43 (0.233) | | 0.394 | 0.289 | 0.305 | 0.011 | 0.001 |
|              |               | Discharge intensity per unit product U44 (0.312) | | 0.357 | 0.321 | 0.207 | 0.074 | 0.041 |
|              |               | Discharge intensity of general industrial solid waste U51 (0.437) | | 0.402 | 0.387 | 0.201 | 0.001 | 0.009 |
|              |               | Discharge intensity of hazardous waste U52 (0.563) | | 0.493 | 0.417 | 0.071 | 0.028 | 0 |
|              |               | Soil compliance rate U61 (0.179) | | 0.217 | 0.302 | 0.327 | 0.134 | 0.02 |
|              |               | Settlement rate of ten thousand tons U62 (0.225) | | 0.385 | 0.259 | 0.216 | 0.102 | 0.038 |
|              |               | Covers an area of strength U63 (0.202) | | 0.282 | 0.402 | 0.201 | 0.106 | 0.009 |
|              |               | Vegetation cover ratio U64 (0.237) | | 0.376 | 0.249 | 0.134 | 0.168 | 0.073 |
|              |               | Groundwater level decline intensity U65 (0.157) | | 0.291 | 0.375 | 0.271 | 0.057 | 0.006 |
|              |               | Investment in environmental protection as a percentage of GDP U71 (0.561) | | 0.451 | 0.387 | 0.101 | 0.051 | 0.01 |
|              |               | Process cost expense ratio U72 (0.439) | | 0.471 | 0.217 | 0.209 | 0.102 | 0.001 |
|              |               | Emission pollutant concentration U81 (0.421) | | 0.378 | 0.291 | 0.183 | 0.107 | 0.041 |
|              |               | Comprehensive water quality index of the region U82 (0.267) | | 0.317 | 0.308 | 0.216 | 0.108 | 0.051 |
| Indicators | Indexes | Values |
|------------|---------|--------|
| Regional atmospheric composite index | U₁₀ | 0.304 0.318 0.194 0.106 0.078 |
| Social benefits U₉ (0.062) | Stakeholder Satisfaction U₉₁ (0.301) | 0.278 0.341 0.228 0.136 0.017 |
| | Changes in residents' quality of life U₉₂ (0.289) | 0.253 0.294 0.204 0.153 0.096 |
| | Number of pollution accidents U₉₅ (0.410) | 0.307 0.281 0.235 0.114 0.063 |
| Response of laws and regulations U₁₀ (0.087) | Implementation of environmental impact assessment U₁₀₁ (0.261) | 0.419 0.372 0.107 0.067 0.035 |
| | Simultaneous execution U₁₀₂ (0.274) | 0.394 0.311 0.273 0.021 0.001 |
| | Completion of total volume control U₁₀₃ (0.293) | 0.284 0.267 0.259 0.103 0.087 |
| | Implementation of emission reduction tasks U₁₀₄ (0.172) | 0.308 0.291 0.236 0.114 0.051 |
| Governance effect U₁₁ (0.108) | Domestic sewage pollutant discharge rate up to the standard U₁₁₁ (0.078) | 0.214 0.297 0.273 0.207 0.009 |
| | Mine drainage pollutant discharge rate up to the standard U₁₁₂ (0.165) | 0.379 0.302 0.214 0.102 0.003 |
| | The emission rate of air pollutants meeting the standards U₁₁₃ (0.133) | 0.307 0.421 0.201 0.067 0.004 |
| | Comprehensive utilization rate of gangue U₁₁₄ (0.152) | 0.512 0.378 0.11 0 0 |
| | Noise emission rate U₁₁₅ (0.109) | 0.391 0.472 0.101 0.036 0 |
| | Settlement remediation rate U₁₁₆ (0.185) | 0.507 0.254 0.201 0.032 0.006 |
| | Comprehensive utilization rate of mine water U₁₁₇ (0.097) | 0.413 0.421 0.107 0.051 0.008 |
| | Comprehensive utilization rate of domestic sewage U₁₁₈ (0.081) | 0.315 0.401 0.253 0.03 0.001 |
| Fund utilization efficiency U₁₂ (0.061) | Expenses for environmental pollution control U₁₂₁ (0.412) | 0.271 0.224 0.326 0.154 0.025 |
| | Investment in environmental protection projects U₁₂₂ (0.375) | 0.328 0.294 0.21 0.107 0.061 |
| | Investment rate of environmental technology innovation U₁₂₃ (0.213) | 0.317 0.288 0.291 0.021 0.083 |
| Response of environmental management U₁₃ (0.099) | Environmental Organization Setup U₁₃₁ (0.228) | 0.613 0.271 0.103 0.013 0 |
| | The emergency response plan U₁₃₂ (0.157) | 0.571 0.41 0.011 0.008 0 |
| | Employee environmental education and training investment rate U₁₃₃ (0.231) | 0.471 0.282 0.247 0 0 |
| | Implementation of the pollutant discharge permit system U₁₃₄ (0.221) | 0.687 0.31 0.003 0 0 |
| | Environmental tax payment U₁₃₅ (0.172) | 0.721 0.279 0 0 0 |

(2) Fuzzy comprehensive evaluation

Step 1: Determine the index set

\[ U = \{u_1, u_2, u_3, u_4, u_5, u_6, u_7, u_8, u_9, u_{10}, u_{11}, u_{12}, u_{13}\} \]

represents the influence indexes in the PPA of the coal mining enterprise, where \( u_1, u_2, u_3, u_4, u_5, u_6, u_7, u_8, u_9, u_{10}, u_{11}, u_{12}, u_{13} \) represent the resource consumption, water pollutant discharge, air pollutant emission, noise emission, solid waste discharge, eco-environmental impact, economic benefit, environmental benefit, social benefit, response.
of laws and regulations, response of governance effect, fund utilization benefit and response of environmental management benefit, respectively.

Step 2: Determine the comment set
\[ V = (v_1, v_2, v_3, v_4, v_5) \] defines the PPA results (excellent, good, medium, ordinary and poor).

Step 3: Establish a membership matrix

Based on the PPA evaluation indexes of a coal mining enterprise in Shaanxi Province, questionnaires were designed and distributed to relevant governmental personnel, experts and scholars in relevant fields and personnel from environmental assessment institutions, the survey data were calculated, and the membership matrix of PPA indexes of this enterprise was obtained, as seen in Table 2.

Step 4: Determine the index weight

The weight of each evaluation index is solved according to the structural entropy weight method, as seen in Table 3.

Step 5: Fuzzy comprehensive evaluation

First, the evaluation results of \( u_1, u_2, u_3, u_4, u_5, u_6, u_7, u_8, u_9, u_{10}, u_{11}, u_{12} \) and \( u_{13} \) are determined as seen in Table 4.

| Serial number | Factors layer                  | Membership | Effectiveness | Evaluation results |
|---------------|--------------------------------|------------|---------------|--------------------|
| 1             | Resource consumption           | 0.368      | 0.428         | 0.155              | 0.049              | 0.000              | 0.388              | good               |
| 2             | Water pollution discharge      | 0.246      | 0.331         | 0.248              | 0.136              | 0.039              | 0.328              | medium             |
| 3             | Air pollution                 | 0.316      | 0.348         | 0.229              | 0.088              | 0.018              | 0.293              | medium             |
| 4             | Noise emissions               | 0.634      | 0.347         | 0.020              | 0.000              | 0.000              | 0.782              | excellent          |
| 5             | Solid waste discharge         | 0.453      | 0.399         | 0.128              | 0.016              | 0.004              | 0.397              | good               |
| 6             | Eco-environmental impact      | 0.317      | 0.311         | 0.222              | 0.117              | 0.032              | 0.235              | medium             |
| 7             | Economic benefits             | 0.460      | 0.312         | 0.148              | 0.073              | 0.006              | 0.520              | excellent          |
| 8             | Environmental benefits        | 0.339      | 0.304         | 0.195              | 0.107              | 0.055              | 0.285              | medium             |
| 9             | Social benefits               | 0.283      | 0.303         | 0.224              | 0.132              | 0.059              | 0.227              | medium             |
| 10            | Response of laws and regulations | 0.354   | 0.311         | 0.219              | 0.073              | 0.044              | 0.309              | medium             |
| 11            | Governance effect             | 0.400      | 0.358         | 0.179              | 0.059              | 0.004              | 0.349              | good               |
| 12            | Fund utilization efficiency   | 0.302      | 0.264         | 0.275              | 0.108              | 0.051              | 0.232              | good               |
| 13            | Response of environmental management | 0.609 | 0.305         | 0.082              | 0.004              | 0.000              | 0.836              | excellent          |

According to the above table, the effectiveness of the maximum membership of “noise emission”, “economic benefit” and “response of environmental management” at the factor layer was greater than 0.5, which could be directly judged using the maximum membership principle. The judgment results were as follows: The evaluation results of the enterprise’s environmental performance—“noise emission”, “economic benefit” and “response of environmental management” were all “excellent”; the effectiveness of the maximum membership of “resource consumption”, “water pollutant discharge”, “air pollution”, “solid waste discharge”, “eco-environmental impact”, “environmental benefit”, “social benefit”, “response of laws and regulations”, “governance effect” and “fund utilization benefit” was smaller than 0.5, which was evaluated using the confidence criterion, specifically as seen in Table 4.

Next, the comprehensive evaluation results of this enterprise are listed in Table 5.
Table 5: Comprehensive Evaluation Results of PPA

| Project | Membership | Effectiveness α | Evaluation results |
|---------|------------|-----------------|--------------------|
| Environmental impact post assessment | excellent: 0.388, good: 0.332, medium: 0.181, general: 0.075, poor: 0.024 | 0.354 | good |

As seen in Table 4, the effectiveness of the maximum membership principle of fuzzy comprehensive evaluation was $0.354 < 0.5$, which needed to be judged according to the confidence criterion: $0.388 + 0.332 > 0.7$, so the final evaluation result of environmental performance of this enterprise was “good”.

The enterprise carried out the construction and operation in strict accordance with the environmental impact assessment report and the requirements replied. Meanwhile, the enterprise fulfilled all kinds of environmental protection formalities according to related laws, regulations and environmental policies, with a relatively complete internal environmental management system and basically perfect ecological restoration measures. In the PPA phase, the environmental impact of coal mining basically coincided with that in the environmental impact assessment phase, with the impacts controlled. The evaluation results basically conformed to the reality.

5. Conclusions

(1) A set of reasonable coal mining post evaluation index system was constructed in this study under the PSR framework. The weight assignment of the index system, which was taken as the study object, was conducted using the structural entropy weight method, thus effectively avoiding the subjectivity of weight assignment. The improved fuzzy comprehensive evaluation method was used to comprehensively judge the index system, and the effectiveness of the maximum membership principle in the fuzzy comprehensive evaluation was verified and improved.

(2) Although the evaluation indexes were screened out in this study based on the PSR framework, the index selection failed to reach the acme of perfection, accompanied by some defects, so it could not reflect the PPA evaluation indexes of coal mining very completely, and the index system construction remained to be improved;

(3) In the constructed evaluation model, the scores given by the experts were processed through the structural entropy weight method, but the evaluation results, which were restricted by the subjectivity of the experts within the industry, could not completely reflect the reality.

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