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A Comparison of Research Methods to Determine the Sustainability of Mineral Resources in Henan Province Based on Cloud Analysis

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Abstract: In order to improve the fuzzy comprehensive evaluation model of mineral resource sustainability and enhance its scientific and objective nature, in this paper, a cloud model-based risk assessment method is introduced to determine the sustainability of mineral resources in a comprehensive comparison, while using a combination of subjective and objective weighting method combining improved hierarchical analysis and the entropy weighting method. Compared with the previous single-assignment evaluation method, the method used in this paper has the advantages of more reasonable determination of weights, more accurate results and better visualization. On this basis, the combined weight method, cloud model method and hierarchical fuzzy evaluation method are organically combined to conduct a comprehensive evaluation of the sustainability of mineral resources in Henan Province. The case analysis shows that the comprehensive evaluation results of the sustainability of mineral resources obtained according to the method are scientifically reasonable and have important reference value and promotion significance for quantitative research in related fields.

Keywords: mineral resource sustainability; improved hierarchical analysis; entropy method; cloud model

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Citation: Gong, S.; Yao, S.; Xi, F.; Liu, J.; Ren, X.; Niu, D.; Ding, J.; Zhang, H.; Wang, J.; Wang, S. A Comparison of Research Methods to Determine the Sustainability of Mineral Resources in Henan Province Based on Cloud Analysis. *Sustainability* **2022**, *14*, 15834. https://doi.org/10.3390/su142315834

Academic Editors: Fangtian Wang, Cun Zhang, Shiqi Liu and Erhu Bai

Received: 30 September 2022
Accepted: 22 November 2022
Published: 28 November 2022

1. Introduction

Henan Province, as shown in Figure 1, is located in the central-eastern part of China, in the middle and lower reaches of the Yellow River, bordered by Anhui Province and Shandong Province to the east, Hebei Province and Shanxi to the north, Shaanxi to the west, and Hubei to the south. Henan Province has a high concentration of mineral resources, with a combination of advantages and a high degree of supporting resources. By the end of 2000, the value of mineral resources in the province was about 1.7 trillion, ranking eleventh in the country [1]. According to the statistics of the geological department of Henan Province, by the end of 2015, 143 kinds of minerals were discovered in the province, accounting for 82.66% of the 173 kinds of minerals discovered nationwide, and 106 kinds of minerals with proven reserves, accounting for 66.67% of the 159 kinds of minerals with proven reserves nationwide. Advantageous minerals, such as molybdenum ore, refractory clay, natural alkali, perlite and others, hold the first place in the country in terms of resource reserves. Coal, iron ore, bauxite, gold ore, silver ore, crystalline graphite, rock salt and coal bed methane are the main mineral reserves that occupy an important position in the country. Henan is an important mineral resource province and mining province; its mining output value for many years ranked in the top five in the country [2]. Given the importance of mining in Henan Province in the industrial development of the province, its sustainable development status has become a common concern of Henan Provincial government and society [3–8]. Therefore, how to evaluate the level of its mineral resource sustainability development has become an important research topic.

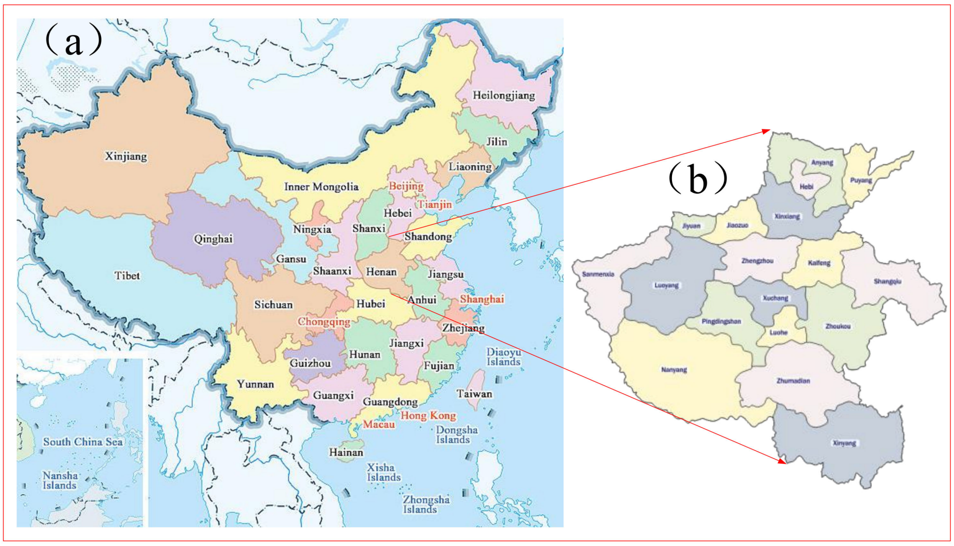

Figure 1. Location map of Henan Province. (**a**) China Map; (**b**) Henan Map.

Since the determination of weights has an important influence on the scientific rationality of the comprehensive evaluation results of multiple indicators, it is particularly important for the comprehensive evaluation of the sustainability of mineral resources. Some scholars have conducted relevant studies on the comprehensive evaluation of mineral resource sustainability, and more results have been achieved in the construction of evaluation models and indicator systems; some papers [9–11] have adopted a single subjective assignment method to determine the weights completely according to expert experience, without considering the numerical characteristics of evaluation indicators, which is too subjective. The literature [12–18] used one or several relevant indicators to determine the weights, which can reflect the problem to some extent, but the consideration is not comprehensive enough and the weights obtained are not accurate. The literature [19–28] used a combination of the expert survey method and hierarchical analysis to determine the weights, where the judgment matrix established by the hierarchical analysis method is quite computationally intensive because it needs to be continuously tested for consistency until it is satisfied. The literature [29,30] used the objective assignment approach to ascertain the weights, which equalizes the value of the indicators and ignores subjective information such as the experience and knowledge of decision makers, which inevitably leads to situations such as unreasonable weighting coefficients. The literature [18,31–34] introduced the cloud model into the evaluation system of mineral resources, but did not make a comparison with other methods and lacked some universality.

Therefore, this work uses a combination of enhanced hierarchical analysis and the entropy weighting method to establish the weight values of each indicator in the sustainability assessment of mineral resources in order to eliminate the shortcomings of the single-assignment method. Further, the fuzzy mathematical method was used to assess the sustainability of mineral resources in Henan Province in a hierarchical and comprehensive manner. Meanwhile, we introduce the evaluation method based on the cloud model into the mineral resource sustainability evaluation system and verify its rationality. On this basis, we first used enhanced hierarchical analysis and the entropy method, combined with fuzzy mathematical formula to assess the sustainability of Henan Province in mineral resources. Then, another cloud model-based mineral resource sustainability evaluation method was used to assess the sustainability of mineral resources in Henan Province. The final evaluation results of the two evaluation methods were compared, and the final evaluation results for the sustainability of mineral resources in Henan Province were obtained; the reasonableness and accuracy of the evaluation method based on the cloud model in the field of mineral resources evaluation were determined.

2. A Comprehensive Evaluation Method for the Sustainability of Mineral Resources Based on Subjective and Objective Weights

2.1. Establish the Weights, Both Subjective and Objective

2.1.1. Determination of Subjective Weights Based on the Progressed AHP Strategy

The progressed AHP strategy, the scalar expansion strategy of progressive investigation, requires rehashed consistency tests on the judgment matrix when utilizing the AHP strategy to calculate the weights. If there are n elements to be compared, the judgment matrix only has to be built to make $n(n-2)/2$ comparative judgments, and the mineral resource sustainability system is a very complex giant multi-layer system with spatio-temporal interaction [28], with more system indicators and larger n values, which is very computationally intensive, and, in addition, the genuine calculation handle regularly leads to challenges in choice making, since the judgment network cannot pass the consistency test. When the improved hierarchical analysis is used to determine the judgment matrix, the constructed judgment matrix is consistent regardless of the scale used, and no consistency test is required, greatly simplifying the computational process, making the method simple and easy to utilize [35,36].

The essential steps of the improved AHP are as follows: n evaluation metrics are compared according to expert experience and ranked according to their importance: $x_1 \geq x_2 \geq \ldots \geq x_n$, and the ratio of the scalar values of x_i and $x_i + 1$ is recorded as t_i, and then the values of the other elements can be calculated according to the transferability. The resulting judgment matrix is shown in Equation (1).

$$R = \begin{bmatrix} 1 & t_1 & t_1t_2 & t_1t_2t_3 & \cdots & t_1t_2 \\ 1/t_1 & 1 & t_2 & t_2t_3 & \cdots & t_2t_3 \\ 1/t_1t_2 & 1/t_2 & 1 & t_3 & \cdots & t_3t_4 \\ 1/t_1t_2t_3 & 1/t_2t_3 & 1/t_3 & 1 & \cdots & t_4t_5 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1/t_1t_2\cdots t_{n-2} & 1/t_2t_3\cdots t_{n-2} & 1/t_3t_4\cdots t_{n-2} & 1/t_4t_5\cdots t_{n-2} & \cdots & t_{n-1} \\ 1/t_1t_2\cdots t_{n-1} & 1/t_2t_3\cdots t_{n-1} & 1/t_3t_4\cdots t_{n-1} & 1/t_4t_5\cdots t_{n-1} & \cdots & 1 \end{bmatrix} \quad (1)$$

The judgment matrix R in Equation (1) is uniformity and does not require a uniform test, and the weights of the indicators derived from it are shown in Equation (2).

$$w_i = \sqrt[n]{\prod_{j=1}^{n} r_{ij}} \Big/ \sum_{i=1}^{n} \sqrt[n]{\prod_{j=1}^{n} r_{ij}} \quad (2)$$

where w_i is the value of the subjective weight of each evaluation index for the sustainability of mineral resources derived; r_{ij} is the scalar value of the ith element in the judgment matrix R compared with the jth element, and its meaning is shown in Table 1.

Table 1. Judgement matrix scale and meaning.

Scale	Implication
1	The two factors are of equal importance
1.2	One factor is slightly more important than the other
1.4	One factor is more important than the other
1.6	One factor is more important than the other
1.8	One factor is more important than the other
Countdown	The factor r_i is compared with r_j to get r_{ji}, then r_j is compared with r_j to get $r_{ji} = 1/r_i$

2.1.2. Objective Weight Determination Based on Entropy Weight Method

According to the fundamental tenets of the information theories, information is a quantity of the orderliness of a system, while entropy is a quantity of the disorderliness [37]. The objective entropy weight obtained by using information entropy does not indicate the importance coefficient of indicators in the actual sense, but the intensity coefficient of each indicator in the competitive sense, which varies depending on the value taken by the evaluation object. The entropy method can accurately reflect the amount of information of mineral resource sustainability evaluation indexes and can effectively solve the problem of large amounts of information and the difficulty in the quantification of mineral resource sustainability evaluation indexes.

The basic idea of the entropy method is as follows: the index system for evaluating the sustainability of mineral wealth is divided into a target level, a criterion level and an element level [28], and the indicator set U = {u_1, u_2, . . . , u_n} of each element layer is a collection of *n* indicators of the evaluation elements. The evaluation set Q = {q_1, q_2, . . . , q_m} is a set consisting of m evaluations, which are usually taken as very strong, strong, moderate, poor and very poor. For each indicator u_i in U doing one evaluation, a fuzzy mapping f(u_i) from U to Q can be obtained, and according to the fuzzy transformation principle, the fuzzy mapping can eventually determine a fuzzy judgment matrix F (Equation (3)) [38].

$$F = \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1m} \\ f_{21} & f_{22} & \cdots & f_{2m} \\ \vdots & \vdots & \cdots & \vdots \\ f_{n1} & f_{n2} & \cdots & f_{nm} \end{bmatrix} \quad (3)$$

Then, the entropy of the ith evaluation indicator is given in the Formula (4).

$$e_i = -\frac{1}{\ln m} \sum_{j=1}^{m} f_{ij} \ln f_{ij} \quad (4)$$

where it is assumed that $f_{ij} \ln f_{ij} = 0$ when $f_{ij} = 0$.

Then, the total entropy value is shown in Equation (5).

$$E = \sum_{i=1}^{n} e_i \quad (5)$$

The entropy weight of the ith evaluation index is shown in Formula (6)

$$v_i = \frac{1}{n - E}(1 - e_i), 0 \le v_i \le 1 \quad (6)$$

2.1.3. Determination of Integrated Weights

The combined weights ai are shown in Equation (7).

$$a_i = \frac{w_i v_i}{\sum\limits_{j=1}^{n} w_j v_j} \quad (7)$$

2.2. Numerical Calculation Using Fuzzy Mathematical Methods

In this paper, the three-level fluffy comprehensive assessment strategy is utilized to comprehensively assess the sustainability of mineral assets.

(1) The fuzzy statistics method is used to determine the affiliation of the factor evaluation levels [27], and then the affiliation of each evaluation index level is normalized to form a matrix F = [f_{ij}](i = 1,2, . . . , *n*; j = 1,2, . . . , m), where f_{ij} is the weight of the ith index at the jth level.

(2) Let the combination weight be A = [a_1,a_2, . . . , a_n], then the evaluation result is shown in Equation (8):

$$B = A \cdot F \tag{8}$$

(3) A weighted average of B yields Equation (9):

$$B' = \sum_{k=1}^{m} kB_k / \sum_{k=1}^{m} B_k \tag{9}$$

where B_k is the element of the kth column in B, which is the judging result of each grade.

(4) The above are the steps of the first-level fuzzy integrated evaluation of the element layer, which finally results in the final evaluation results of the ten elements of the element layer, then the second-level fuzzy integrated evaluation of the criterion layer, which results in the fuzzy integrated evaluation results of the development force and coordination force of the criterion layer, and, finally, the third-level fuzzy integrated evaluation of the target layer, which results in the evaluation results of the sustainability of the target layer. The steps of the comprehensive evaluation of mineral resource sustainability at all levels are shown in Figure 2.

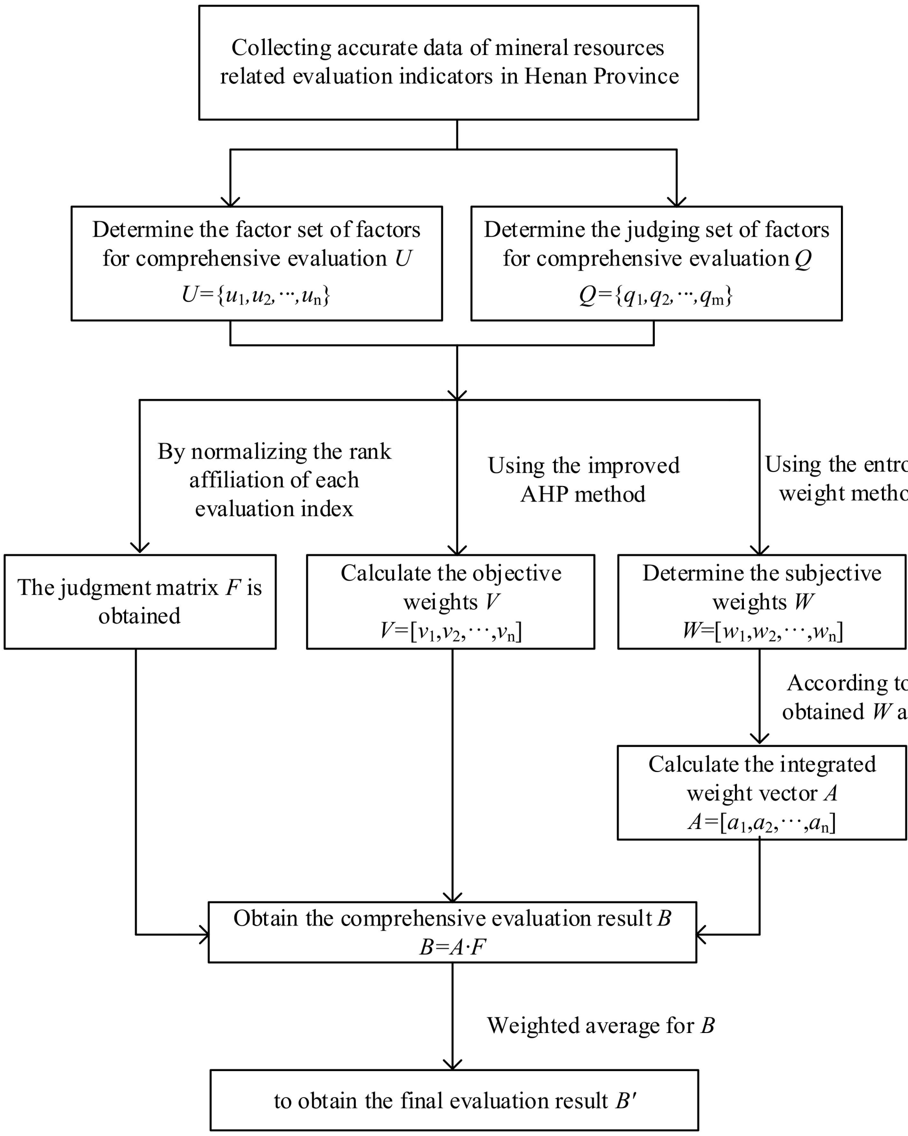

Figure 2. Steps of comprehensive evaluation of mineral resource sustainability at all levels.

2.3. Comprehensive Evaluation of the Sustainability of Mineral Resources in Henan Province Based on Subjective and Objective Weights

The data collection with 2013 as the base year was conducted through relevant research literature, policy documents, statistical data, and website information. These include more than 30 domestic and foreign research literature; more than 100 policy documents on mineral resource management and mining investment from 31 provinces. From this, we derived the evaluation indexes and evaluation criteria for the sustainability evaluation of mineral resources in Henan Province as shown in Table 2. Since the mineral resource sustainability evaluation index system contains three levels, 10 elements and 34 indicators, the calculation is large when making a comprehensive judgment and limited to space; therefore, only the first element—the comprehensive judgment of resource endowment and development conditions—is used as an example for detailed explanation.

Table 2. Table of evaluation indicators and evaluation criteria for the sustainability of mineral resources in Henan Province.

Element Name	Indicator Name	Unit of Measurement	Indicator Value/Indicator Description	Evaluation Criteria (National Average)
U_{11}: Resource endowment and development conditions	U_{111} The potential value of major mineral holdings per person	Million CNY/person	1.83	2.46
	U_{112} Mineral Resource Pressure Index	%	Energy Minerals: 98.5 Metal Minerals: 59.7 Non-metallic minerals: 3	Energy Minerals: 85.6 Metal Minerals: 65.8 Non-metallic minerals: 2
	U_{113} Aggregation of major mineral resources	Million CNY/km^2	1073.56	889.69
	U_{114} Degree of Geological Exploration		Low and uneven level of exploration	
	U_{115} Mineral Resource Development Conditions		The location of the mine is good and the development conditions are excellent	
U_{12}: Development of and benefit to economy	U_{121} GDP per capita	CNY	42,575	53,935
	U_{122} GDP per capita annual growth rate	%	7.5	6.7
	U_{123} Net fixed assets per capita	Million CNY	3.75	4.39
	U_{124} Hundred CNY Mining Original Value of Fixed Assets Realized Profit Tax	CNY	17.65	7.54
	U_{125} Hundred CNY of total mining output realized profits and taxes	CNY	12.48	13.52
	U_{126} Investment elasticity of mining output		0.086	0.482
U_{13}: Development of society and quality of life	U_{131} Natural population growth rate	%	6.12	5.86
	U_{132} Mining industry personnel growth rate	%	−12.25	−10.06
	U_{133} Per capita income	CNY	Cities and towns 27,232.92	Cities and towns 33,616.2
			Rural 11,696.74	Rural 12,363.4
	U_{134} Engel's coefficient	%	Cities 23.18	Cities 29.30
			Rural 26.34	Rural 32.24
U_{14}: Environmental impact	U_{141} "Three waste" pollution index	%	48.59	30.9

Table 2. *Cont.*

Element Name	Indicator Name	Unit of Measurement	Indicator Value/Indicator Description	Evaluation Criteria (National Average)
U_{15}: Intelligence level	U_{151} School-age children enrollment rate	%	100.0	99.9
	U_{152} Growth rate of scientific and technical personnel in the mining industry	%	−1.58	−1.46
	U153 Science and Technology Contribution Growth Rate	%	1.3	2.0
U_{21}: Resource conversion efficiency	U_{211} Mineral Resource Recovery Rate	%	80	70
	U_{212} Comprehensive utilization rate of co-associated mineral resources	%	90	20
	U_{213} Succession resource support strength	%	35.8	30.3
U_{22}: Economic Harmonization	U_{221} The proportion of non-mining value added	%	93.3	96.9
	U_{222} Mining earnings growth	%	106.1	−4.4
	U_{223} Energy consumption of 10,000 CNY GDP	Tons of standard coal	0.571	0.586
U_{23}: Social coherence	U_{231} Mining Employment Rate	%	97.0	95.98
	U_{232} Social Security Coverage	people	Number of health technicians per 10,000 population: 57.4	Number of health technicians per 10,000 population: 61.2
		%	Growth rate of premium income by category: 14.69	Growth rate of premium income by category: 16.41
U_{24}: Environmental Harmony	U_{241} Environmental pollution control elasticity coefficient	%	307.6	58.9
	U_{242} Comprehensive treatment rate of "three wastes"	%	38.68	40.21
	U_{243} Land reclamation rate	%	8	81
U_{25}: Intellectual coordination	U_{251} Education spending as a percentage of GDP	%	4.67	4.87
	U_{252} Number of college students in 10,000	Million people	200.47	2695.8
	U_{253} Science and technology activity expenses as a percentage of GDP	%	1.25	2.11
	U_{254} Mining Management Level		better	Moderate

According to the table, U = {potential value of major mineral reserves per capita, mineral resource pressure index, concentration of major mineral resources, geological exploration degree, mineral resource development condition} and Q = {very strong, strong, medium, poor, very poor}. The indicators of resource endowment and development conditions are classified into five grades according to the evaluation set Q. The basic steps of the comprehensive evaluation of the level of resource endowment and development conditions are shown below.

2.3.1. Improved Hierarchical Analysis to Determine Subjective Weights

(1) In accordance with the expert opinions and related information, the following sequential relationships were obtained for each evaluation index: potential value > exploration degree > development conditions > resource aggregation degree > pressure index.

(2) The relative importance of each indicator can be determined through the expert survey: $r_{12} = 1.2$, $r_{23} = 1.6$, $r_{34} = 1.7$, $r_{45} = 1.8$.

(3) The judgment matrix R is derived from Equation (1).

$$R = \begin{bmatrix} 1 & 1.2 & 2.04 & 3.264 & 5.8752 \\ 1/1.2 & 1 & 1.7 & 2.72 & 4.896 \\ 1/2.04 & 1/1.7 & 1 & 1.6 & 2.88 \\ 1/3.264 & 1/2.72 & 1/1.6 & 1 & 1.8 \\ 1/5.8752 & 1/4.896 & 1/2.88 & 1/1.8 & 1 \end{bmatrix}$$

(4) Using Equation (2), the subjective weight esteem of each index can be obtained: w_1 = 0.367, w_2 = 0.277, w_3 = 0.180, w_4 = 0.113, w_5 = 0.063. The subjective weight values of potential value, degree of exploration, development condition, resource aggregation and pressure index are indicated in order.

2.3.2. Find the Evaluation Matrix F

According to the data in Table 2, the affiliation degree of each index is obtained by the method of fuzzy statistics and then normalized to obtain the judgment matrix of resource endowment and development conditions.

$$F = \begin{bmatrix} 0.00 & 0.00 & 0.60 & 0.40 & 0.00 \\ 0.10 & 0.30 & 0.50 & 0.10 & 0.00 \\ 0.40 & 0.40 & 0.20 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.20 & 0.30 & 0.50 \\ 0.50 & 0.40 & 0.10 & 0.00 & 0.00 \end{bmatrix}$$

2.3.3. Determination of Objective Weights by Entropy Power Method

(1) According to the matrix F and Equation (4), the entropy of each indicator can be found as: e_1 = 0.418, e_2 = 0.0.726, e_3 = 0.656, e_4 = 0.640, e_5 = 0.586.

(2) According to Equation (5), the total entropy value is: E = 3.026.

(3) According to Equation (6), the objective weights of potential value, exploration degree, development condition, resource aggregation and pressure index can be obtained: v_1 = 0.295, v_2 = 0.139, v_3 = 0.174, v_4 = 0.182, v_5 = 0.210.

2.3.4. Finding the Combination Weights

According to Equation (7), the combined weight vector is A = [0.509, 0.184, 0.146, 0.099, 0.06], which represents the weight values of potential value, exploration degree, development condition, resource aggregation and pressure index in order, and this weight is the final weight of resource endowment and development conditions obtained by the combination of improved hierarchical analysis and the entropy weight method.

2.3.5. Calculating Judgment Results

Judgment results are calculated according to Equation (8): B_{11} = [0.107, 0.138, 0.453, 0.252, 0.049].

2.3.6. Weighted Average for B_{11}

From Equation (9), we obtain B'_{11} = 2.995, which is the final evaluation result of resource endowment and development conditions, and $B'11$ is between 2 and 3, that is, resource endowment and development conditions are between "strong" and "medium". The above is the comprehensive evaluation of mineral resource endowment and development conditions in Henan Province, and the evaluation steps of the remaining nine indicators in the element layer are similar to them. The final evaluation results of each indicator in the first-level fuzzy comprehensive evaluation are:

B_{12} = (0.160, 0.380, 0.353, 0.038, 0.070); B_{13} = (0.000, 0.385, 0.260, 0.270, 0.085);
B_{14} = (0.098, 0.195, 0.323, 0.260, 0.125); B_{15} = (0.020, 0.250, 0.310, 0.270, 0.150);
B_{21} = (0.290, 0.060, 0.145, 0.160, 0.345); B_{22} = (0.340, 0.283, 0.100, 0.160, 0.118);
B_{23} = (0.320, 0.140, 0.313, 0.105, 0.123); B_{24} = (0.160, 0.385, 0.260, 0.145, 0.050);
B_{25} = (0.000, 0.195, 0.333, 0.100, 0.373).

Organize the evaluation results corresponding to the first-level evaluation indicators into a matrix.

(1) Resource base development condition matrix R_1

$$R_1 = \begin{bmatrix} 0.107 & 0.138 & 0.454 & 0.252 & 0.049 \\ 0.160 & 0.380 & 0.353 & 0.038 & 0.070 \\ 0.000 & 0.385 & 0.260 & 0.270 & 0.085 \\ 0.098 & 0.060 & 0.145 & 0.160 & 0.345 \\ 0.020 & 0.250 & 0.310 & 0.270 & 0.150 \end{bmatrix}$$

(2) Resource coordination and transformation capability matrix R_2

$$R_2 = \begin{bmatrix} 0.290 & 0.060 & 0.145 & 0.160 & 0.345 \\ 0.340 & 0.283 & 0.100 & 0.160 & 0.118 \\ 0.320 & 0.140 & 0.313 & 0.105 & 0.123 \\ 0.160 & 0.385 & 0.260 & 0.145 & 0.050 \\ 0.000 & 0.195 & 0.333 & 0.100 & 0.373 \end{bmatrix}$$

According to the two-level fuzzy integrated evaluation, the evaluation results of development and coordination are B_1 = (0.066, 0.294, 0.321, 0.220, 0.099) and B_2 = (0.256, 0.221, 0.207, 0.140, 0.176). The weighted average gives B'_1 = 2.992 and B'_2 = 2.759, which is the final evaluation result of the developmental and coordination power. According to the three-level fuzzy integrated evaluation, the final evaluation result of the sustainability of mineral resources in the target layer of Henan Province can be obtained as B = (0.142, 0.265, 0.275, 0.188, 0.130). The weighted average is B' = 2.899, which is the final evaluation result of the sustainability of mineral resources in Henan Province; B' is between 2 and 3, so the sustainability of mineral resources in Henan Province is between "strong" and "medium".

2.4. Comprehensive Evaluation Results of the Sustainability of Mineral Resources in Henan Province with a Combination of Subjective and Objective Weights

In order to thoroughly research the features and deficiencies of each evaluation element in the mineral resource sustainability index system of Henan Province, the weighted average of B_{12} to B_{25} is obtained as follows: B'_{12} = 2.480, B'_{13} = 3.005, B'_{14} = 3.120, B'_{15} = 3.280, B'_{21} = 3.210, B'_{22} = 2.434, B'_{23} = 2.571, B'_{24} = 2.540 and B'_{25} = 3.650. They represent the final evaluation results of economic development and efficiency, social development and quality of life, environmental impact, intellectual level, resource conversion efficiency, economic coordination, social coordination, environmental coordination and intellectual coordination, in that order. Figure 3 shows the rating evaluation factors of each index of the sustainability of mineral resources in Henan Province. In addition, there is a detailed explanation of each indicator, as shown in Table 3.

Table 3. Explanatory notes of each evaluation index.

Evaluation Objectives	Level I Indicators	Indicator Name	Level II Indicators	Indicator Name
Sustainability of mineral resources in Henan Province U	Resource base development conditions	U_1	Resource endowment and development conditions	U_{11}
			Economic Development and Benefits	U_{12}
			Social development and quality of life	U_{13}
			Environmental impact	U_{14}
			Intelligence level	U_{15}
	Resource coordination and transformation capabilities	U_2	Resource conversion efficiency	U_{21}
			Economic Harmonization	U_{22}
			Social coherence	U_{23}
			Environmental Harmony	U_{24}
			Intellectual coordination	U_{25}

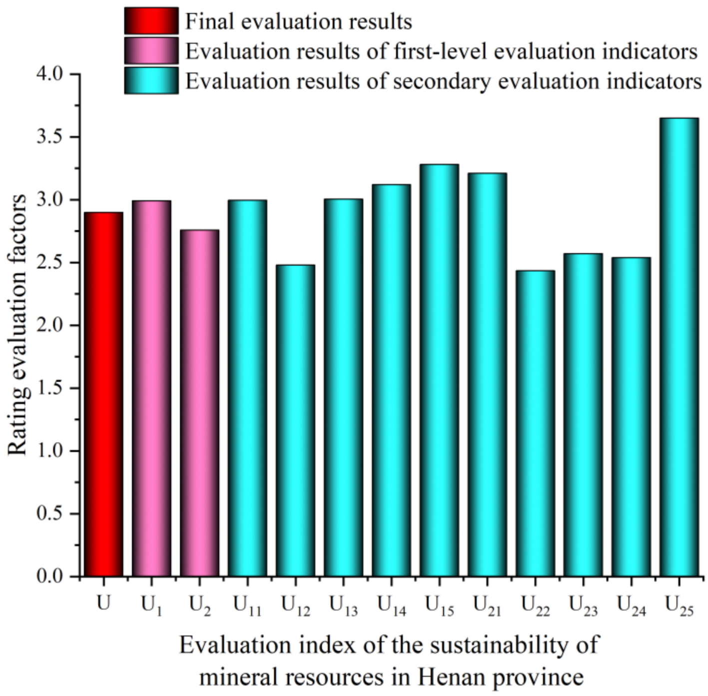

Figure 3. Evaluation factors of each index level of the sustainability of mineral resources in Henan Province.

3. A Comprehensive Evaluation Method of Mineral Resource Sustainability Based on a Cloud Model

3.1. Principle of Comprehensive Evaluation of Mineral Resource Sustainability Based on a Cloud Model

3.1.1. Cloud Model Concept

A cloud is a natural language representation of some qualitative concept. A cloud is a model of uncertainty transformation between some qualitative concept represented by natural language values and a quantitative representation that is intuitive and universal. It mainly reflects conceptual uncertainty, i.e., vagueness and randomness. The basic idea of the cloud model is that U is a quantitative domain expressed in exact values and C is a qualitative concept on U. If some quantitative value x is both a value in U and a random realization of C, x has determinant $\mu(x) \in [0, 1]$ for C, and the distribution of $\mu(x)$ satisfies μ: $U \to [0, 1]$, $x \in U$ with $x \to \mu(x)$, then each x is a cloud droplet and the distribution of x over the domain U of the argument is called a cloud. The cloud model is mainly expressed in terms of three basic numerical characteristic values: Expectation Ex, i.e., the expectation of the distribution of cloud drops in the theoretical domain space; Entropy En, i.e., the uncertainty and ambiguity of the distribution of cloud drops; Hyperentropy He, i.e., the entropy of the entropy, which indicates the degree of dispersion of the clouds in the cloud diagram. The greater the hyperentropy, the greater the thickness of the clouds; for example, when setting the number of cloud drops to 2000, C = (0.6, 0.2, 0.01, 2000), of which the cloud diagram is shown in Figure 4.

3.1.2. Principles of Cloud Model Evaluation Based on Combined Weights

In the application of cloud theory models, we usually use forward cloud generators and inverse cloud generators to achieve the conversion between qualitative index description and quantitative data. In this paper, the inverse cloud generator (Figure 5) is used to generate a comprehensive cloud to be evaluated and a standard evaluation cloud to assess the service status of the roadbed to achieve a more scientific, objective, convenient and intuitive judgement of the roadbed condition. The steps of the inverse cloud generator algorithm are.

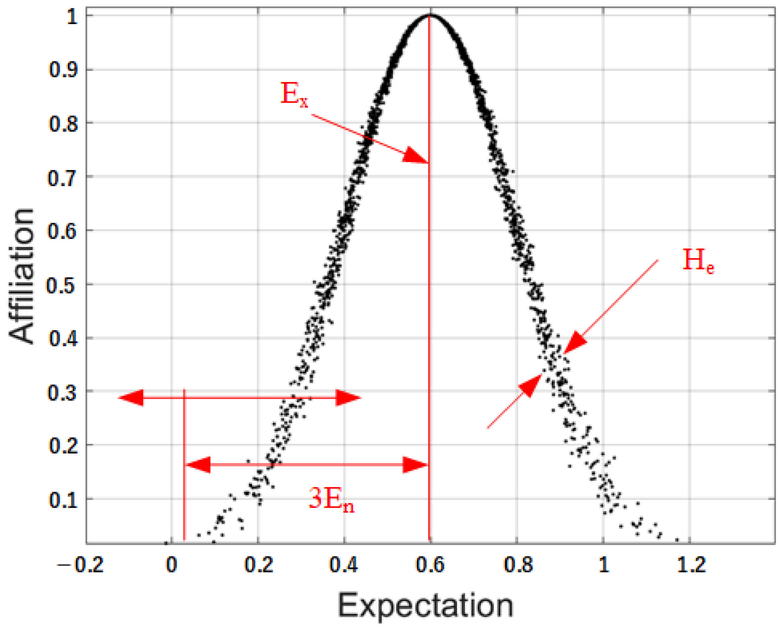

Figure 4. Example cloud model.

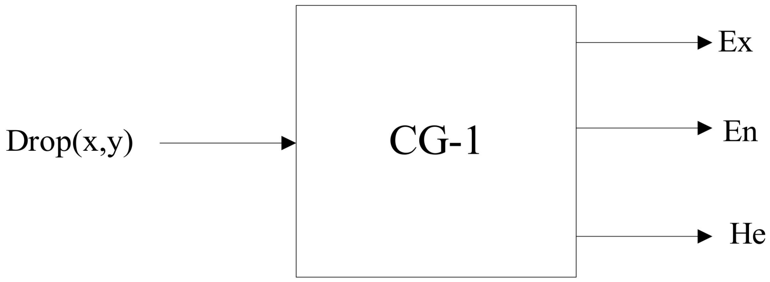

Figure 5. Reverse Cloud Launcher.

(1) Calculate the sample mean

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{10}$$

(2) Calculate the sample variance

$$S^2 = \frac{1}{n-1}\sum_{i=1}^{n} (x_i - \overline{X})^2 \tag{11}$$

(3) Calculate expectations

$$d = \frac{1}{n}\sum_{i=1}^{n} |x_i - \overline{X}| \tag{12}$$

(4) Calculate first-order sample center distance

$$d = \frac{1}{n}\sum_{i=1}^{n} |x_i - \overline{X}| \tag{13}$$

Then the sample entropy

$$E_n = \sqrt{\frac{\Pi}{2}} \times \frac{1}{n}|x_i - \overline{X}| \tag{14}$$

(5) Calculate the sample hyperentropy

$$H_e = \sqrt{S^2 - \sqrt{E_n^2}} \tag{15}$$

The specific steps of the cloud model evaluation method based on the combination of weights for the characteristics of mineral resource potential in Henan Province are as follows.

Step 1: A combination of the improved hierarchical analysis and the entropy weighting method is calculated to obtain a vector set of indicator weights.

Step 2: For each assessment indicator, establish the corresponding rubric set and its value range, and generate the standard evaluation cloud corresponding to each level.

Step 3: Using the inverse cloud generator to find Ex, En and Ee of the existing data, the eigenvalues of the three clouds are generated by calculating the average of n sample points according to the inverse cloud generator algorithm.

Step 4: Generate a standard evaluation cloud, a level-one evaluation cloud, a level-two evaluation cloud and a comprehensive evaluation cloud.

Step 5: Calculate the similarity between the comprehensive evaluation cloud and the standard evaluation cloud of the corresponding attributes, from which the overall comparison of the cloud map can be carried out to assess the ranking of the mineral resource potential of Henan Province. The whole assessment process is shown in Figure 6.

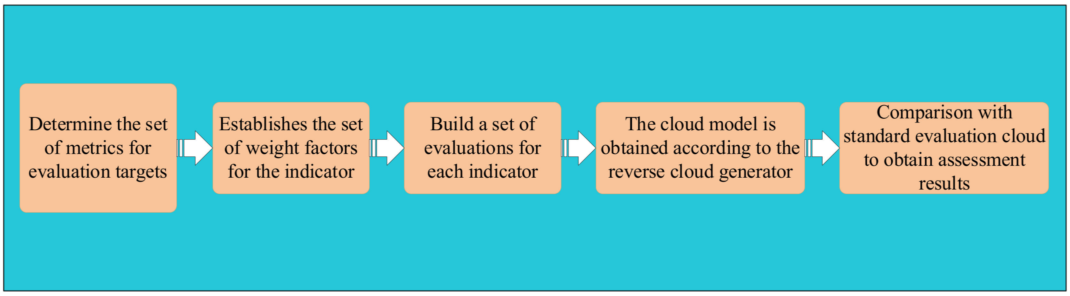

Figure 6. Evaluation process.

3.2. Comprehensive Evaluation Results of the Sustainability of Mineral Resources in Henan Province Based on a Cloud Model

3.2.1. Generate a Standard Cloud

Similarly, using expert evaluation data of mineral resource potential in Henan Province, according to the determined five grade intervals, five grade evaluation parameters are obtained by cloud generator. Then, five levels of standard cloud images are generated by MATLAB, as shown in Figure 7.

3.2.2. Generate a Cloud Map

Through the resource endowment and development conditions in Figure 8, a cloud map is generated.

The drawing results of the ten-element index level evaluation cloud chart are shown in Figure 9.

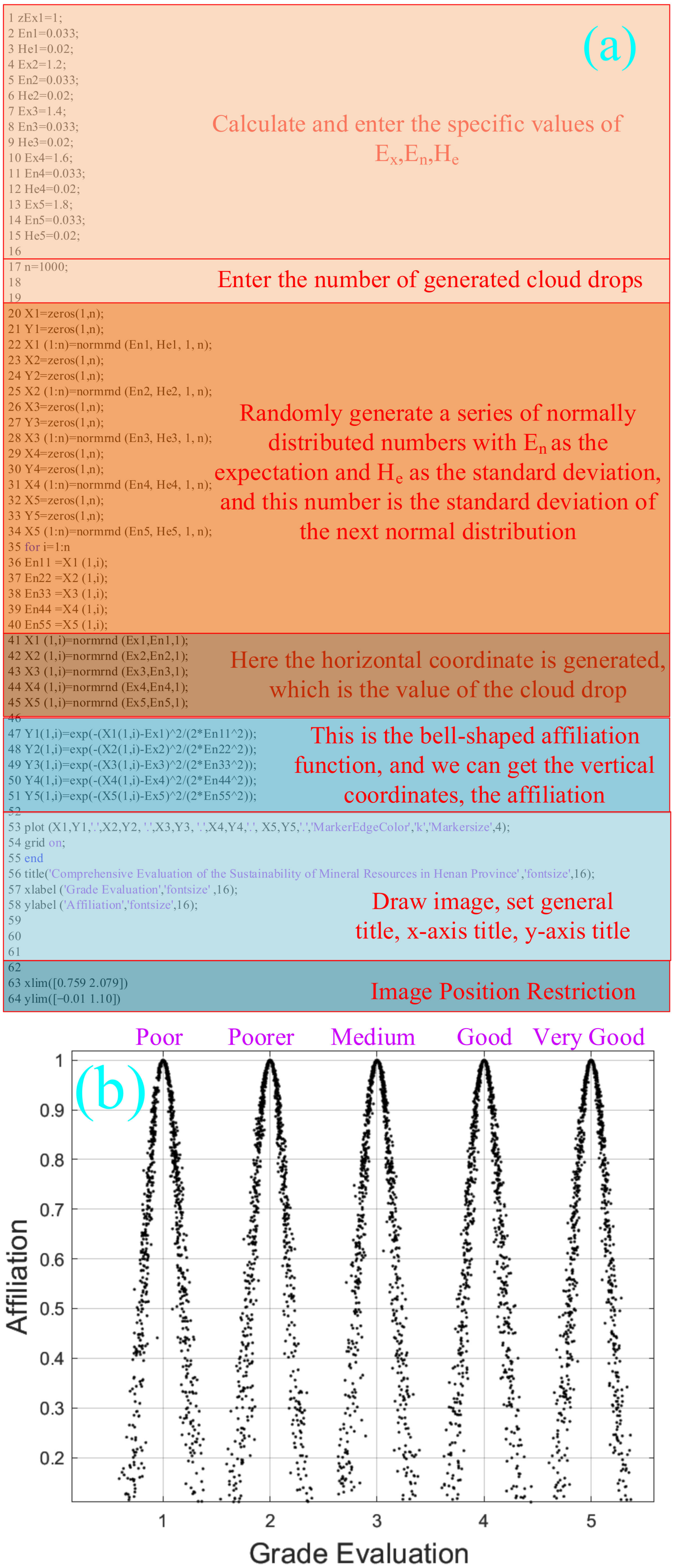

Figure 7. Code interpretation and final generation diagram for building evaluation criteria cloud. (**a**) Explanation of building evaluation criteria cloud code; (**b**) Generated standard evaluation charts.

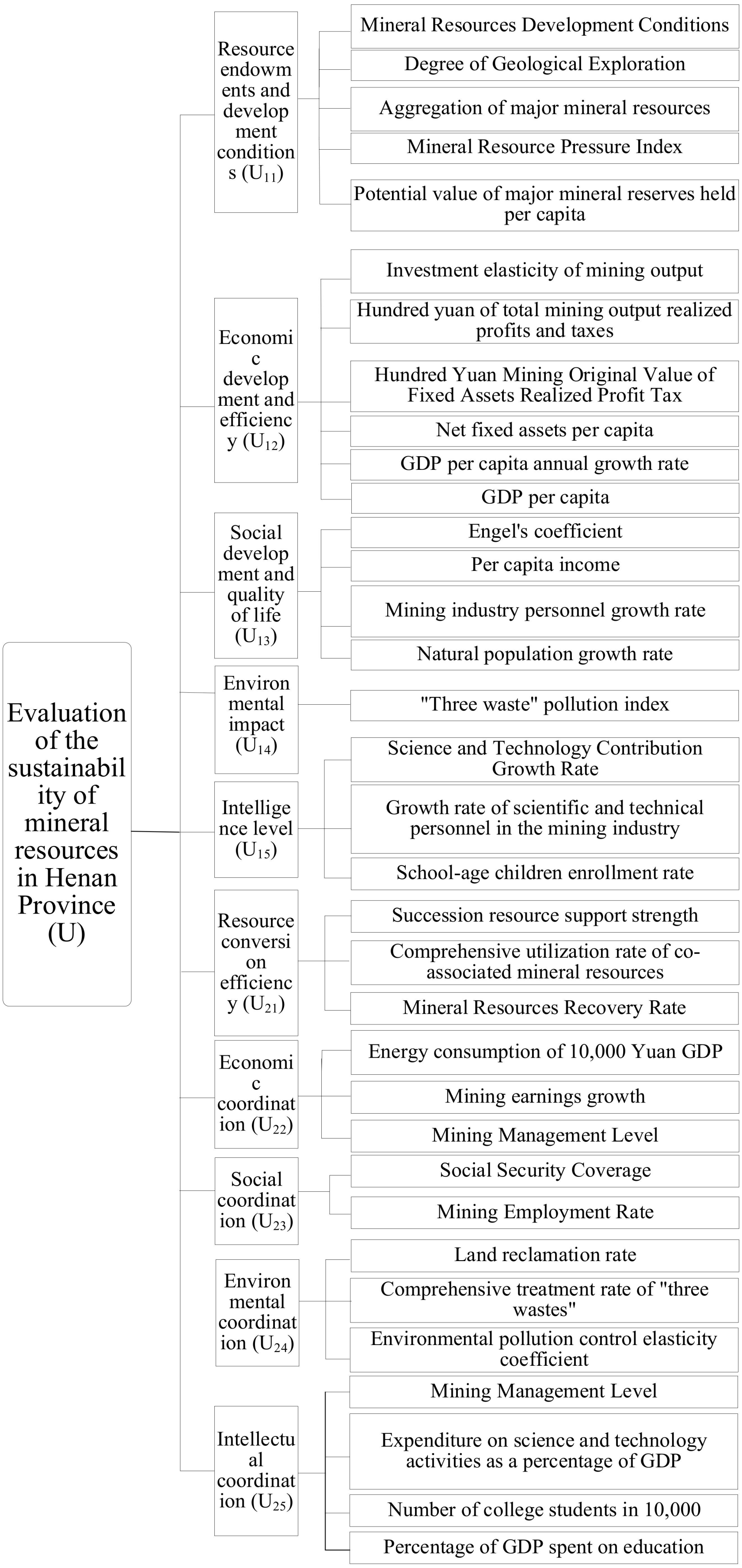

Figure 8. The evaluation index map of mineral resource sustainability in Henan Province.

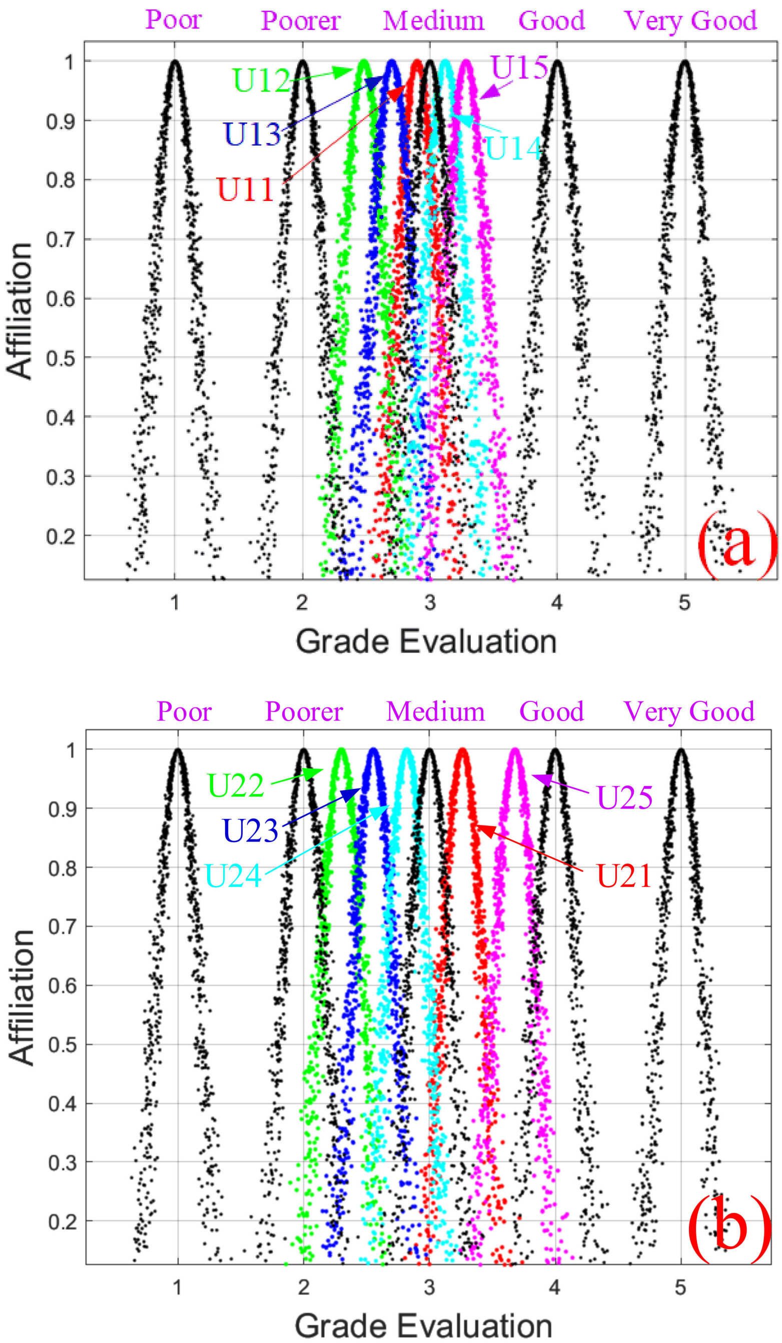

Figure 9. First-level evaluation cloud. (**a**) Evaluation results of resource base development conditions; (**b**) Evaluation results of resource coordination and transformation capacity.

The secondary evaluation cloud map is drawn by the same principle as the primary evaluation cloud, as shown in Figure 10.

Finally, the comprehensive evaluation cloud map of the sustainability of mineral resources in Henan Province is obtained, as shown in Figure 11.

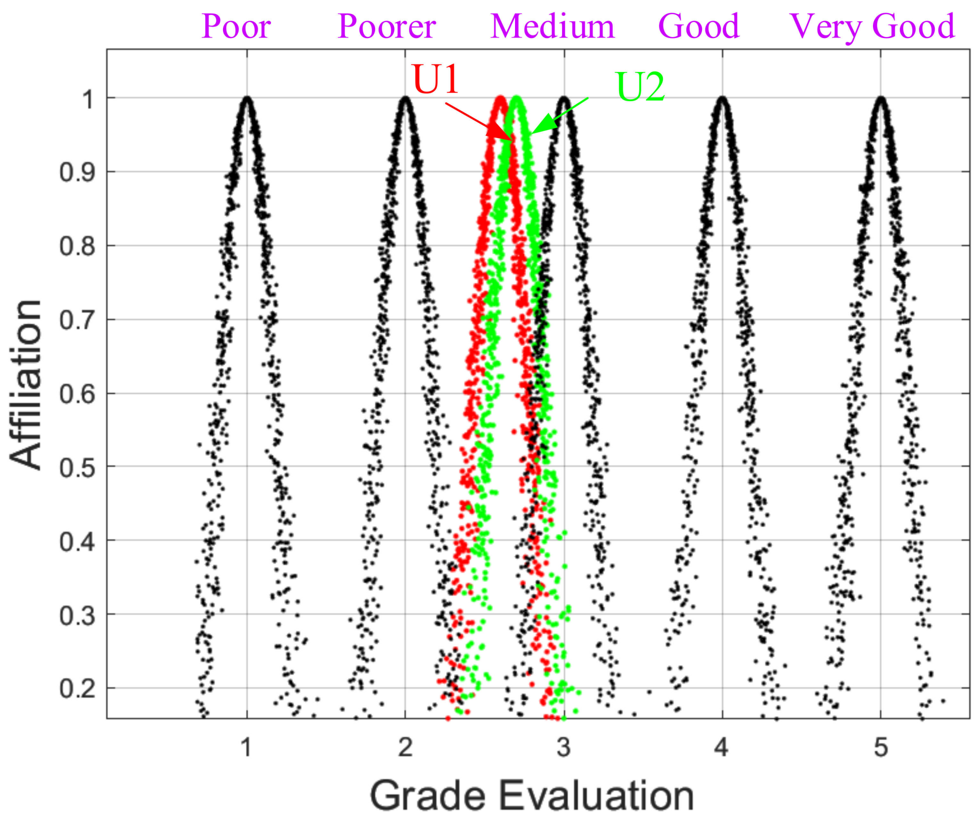

Figure 10. Secondary evaluation cloud.

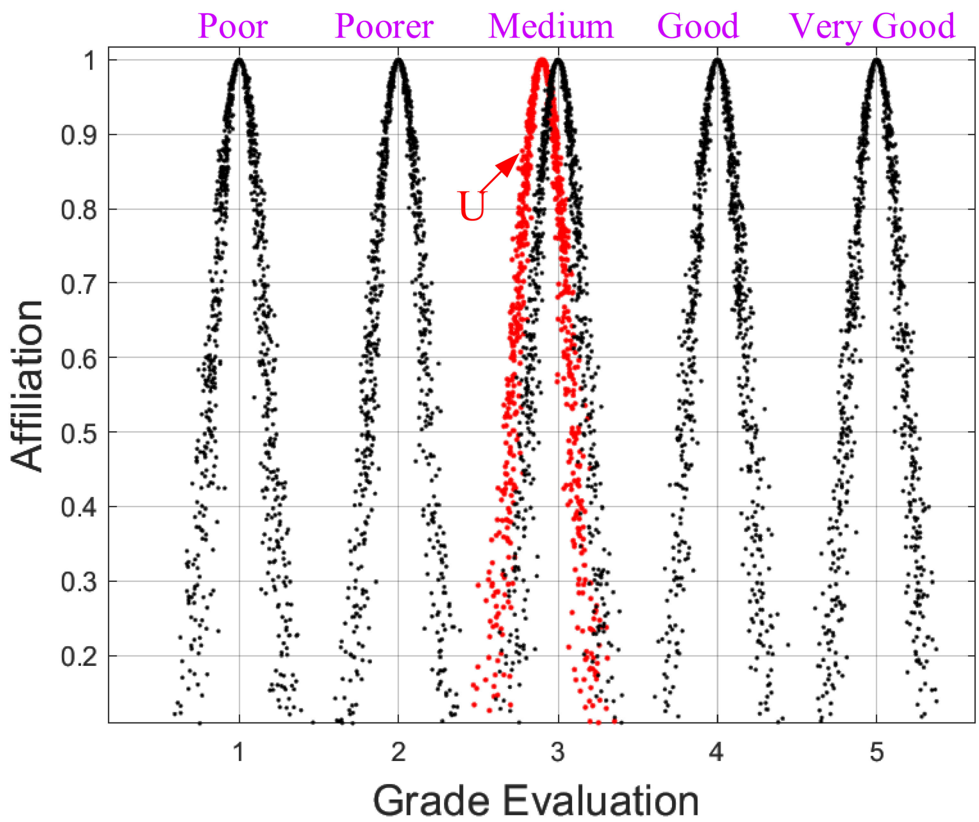

Figure 11. Comprehensive evaluation cloud.

4. Comparison of Two Evaluation Results

The evaluation results of the indicators at all levels are compared between the two evaluation results, as shown in Table 4. After comprehensive analysis, in Figure 3, the evaluation factors of indicators U12 and U23 tend to be close to 2, i.e., the rating is near "strong", while the evaluation factors of indicators U15 and U25 tend to be close to 4, maintaining the rating near "poor", and the rest of the indicators tend to be "medium". According to the above comprehensive evaluation results, Henan Province is considered to have medium mineral resource sustainability on the national scale, and its advantages are economic development and efficiency and social coordination, mainly in the form of high per capita GDP per capita growth rate, a high mining employment rate and social security coverage rate. The deficiencies are intellectual level and intellectual coordination, mainly in the form of serious loss of scientific and technological personnel in the mining industry, low growth rate of scientific and technological contribution, the amount of college students per 10,000 people is lower than the national average, and the ratio of scientific and technological activities to GDP is low. If we can further improve the mining intelligence situation, it will help to improve the level of sustainability of mineral resources in Henan Province. Meanwhile, as shown in Figure 12, comparing the results of mineral resource sustainability based on the subjective and objective weight method and the evaluation of mineral resource sustainability based on the cloud model reveals that, although there are some differences between the two, the evaluation results are generally highly consistent. The above evaluation results are basically consistent with the actual situation, as investigated by relevant experts from Henan Provincial Bureau of Statistics, the Department of Land and Resources, and the Environmental Protection Bureau, indicating that the evaluation method and evaluation results of this paper are scientific and reasonable.

Table 4. Comparison of evaluation results of different methods.

Sustainability Evaluation Methodology	Fuzzy Comprehensive Evaluation Method	Cloud Model Method
U Sustainability level of mineral resources in Henan Province	Somewhere between strong and medium	Somewhere between strong and medium
U1 indicator level	Somewhere between strong and medium	Somewhere between strong and medium
U2 indicator level	Somewhere between strong and medium	Somewhere between strong and medium
U11 indicator level	Somewhere between strong and medium	Somewhere between strong and medium
U12 indicator level	Somewhere between strong and medium	Somewhere between strong and medium
U13 indicator level	Between moderate and poor	Somewhere between strong and medium
U14 indicator level	Between moderate and poor	Between moderate and poor
U15 indicator level	Between moderate and poor	Between moderate and poor
U21 indicator level	Between moderate and poor	Between moderate and poor
U22 indicator level	Somewhere between strong and medium	Somewhere between strong and medium
U23 indicator level	Somewhere between strong and medium	Somewhere between strong and medium
U24 indicator level	Somewhere between strong and medium	Somewhere between strong and medium
U25 indicator level	Between moderate and poor	Between moderate and poor

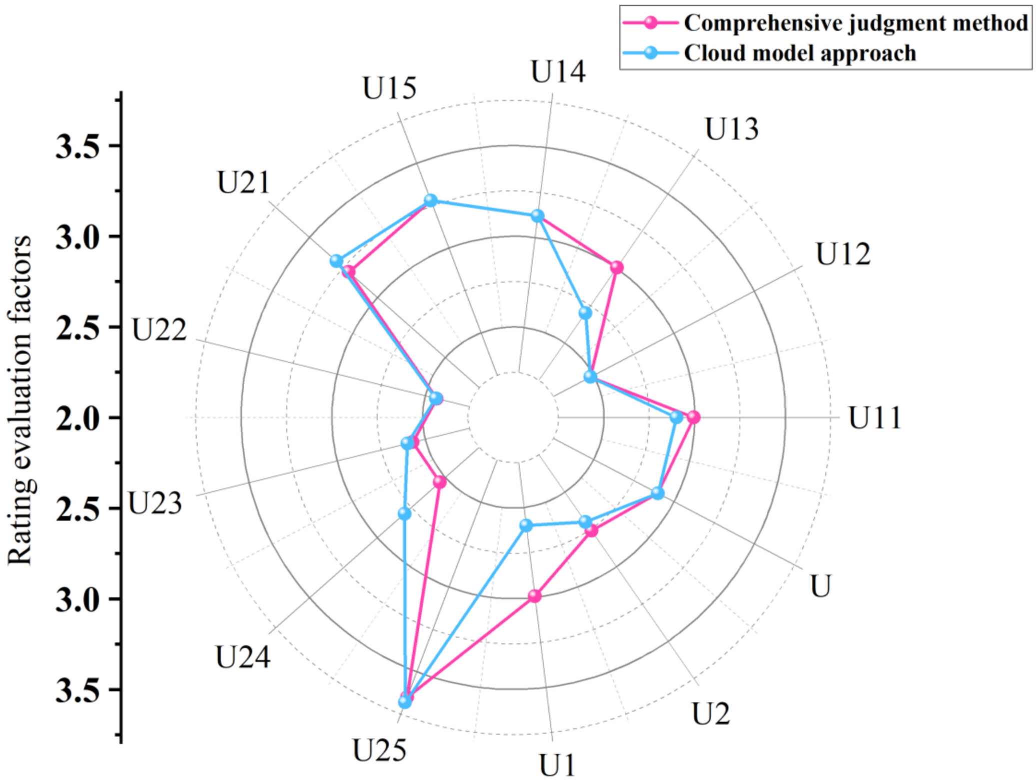

Figure 12. Comparative radar chart of the two evaluation results.

5. Conclusions

1. Taking into account the significance of weights in the integrated assessment, this article has optimized the previous single-assignment method on the basis of the improved graded analysis method and entropy power method combined with the subjective–objective combination weight method to modify the mineral resource sustainability evaluation model, so that the subjective and objective are unified, and the distribution method is more rational and more realistic.
2. In view of the multi-level and multi-indicator characteristics of the mineral resource sustainability evaluation index system, the improved AHP method is used to identify the weights, and compared with the traditional AHP approach, the judgment matrix does not need to be tested for consistency again, which greatly reduces the calculation volume in the evaluation process.
3. The weighted average of the resulting comprehensive evaluation results makes the final evaluation results more intuitive and easier for statistics and analysis.
4. The final result of this paper is a comparative analysis among the indicators of mineral resource sustainability in the same region within the same time period, so as to facilitate the identification of the strengths and weaknesses of each indicator in the region. This model can also be used to assess the sustainable nature of mineral resources among different regions in the same time period horizontally, or to rate the dynamic development of mineral resource sustainability in the same region in different time periods vertically.
5. We evaluated the sustainability of mineral resources in Henan Province using the introduced cloud model approach. Then, the results of the derived evaluation indicators at all levels were compared with the evaluation results at all levels derived from the comprehensive evaluation method of mineral resource sustainability based on subjective and objective weights, and it was found that only a few indicators had very small errors in the evaluation results and were within the acceptable range. Therefore, the evaluation of mineral resources using the cloud model is a reasonable and acceptable method, and the evaluation results are accurate and have better visibility.

Author Contributions: Conceptualization, S.G. and S.Y.; methodology, J.L.; software, X.R. and J.L., H.Z.; validation, S.G., S.Y. and F.X.; formal analysis, D.N.; investigation, J.D.; resources, S.W.; data curation, J.W.; writing—original draft preparation, S.G., S.Y. and J.L.; writing—review and editing, S.G.; visualization, X.R.; supervision, S.G.; project administration, F.X.; funding acquisition, S.G. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the Fundamental Research Funds for the Universities of Henan Province (grant No. NSFRF200332), China Postdoctoral Science Foundation (grant No. 2021M701100), Key Research and Development and Promotion of Special (Science and Technology) Project of Henan Province (grant Nos. 212102310379 and 212102310603), National Natural Science Foundation of China (grant Nos. 41907402 and 51604093), the Key Scientific Research Project Fund of Colleges and Universities in Henan Province (grant Nos. 21A610005 and 20B440001), the research fund of Henan Key Laboratory for Green and Efficient Mining & Comprehensive Utilization of Mineral Resources, Henan Polytechnic University (grant Nos. KCF2210) and the Doctoral Foundation of Henan Polytechnic University (grant No. B2019-22).

Data Availability Statement: Data will be made available on request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Henan Provincial Department of Land and Resources, Mineral Resources Master Plan of Henan Province (2016–2020). 2017. Available online: https://www.henan.gov.cn/2017/12-27/249361.html (accessed on 29 September 2022).
2. Geology and Mineral Bureau of Henan Province. Overview of Mineral Resources in Henan Province. 2009. Available online: http://www.onlinece.com.cn/ShowArticle.asp?ArticleID=4293 (accessed on 29 September 2022).
3. Yu, K. Analysis of Grey Correlation Degree between Mining Structure and Economic Growth in Henan Province. In Proceedings of the 2021 5th International Conference on Economics, Management Engineering and Education Technology, Toronto, ON, Canada, 4–6 June 2021.
4. Li, X.; Yang, Y.; Meng, Q. Comparative Analysis of Three Governance Modes for Resource-Based Urban Sustainability in China Based on Residents' Perception: An Empirical Study of Pingdingshan City, Henan Province, China. *Sustainability* **2021**, *13*, 13658. [CrossRef]
5. Li, M. Research on the Sustainable Development Strategy of Forestry Cultural Heritage Sites in Henan Province Based on the Analysis of Big Data. *J. Phys. Conf. Ser.* **2021**, *1744*, 032177. [CrossRef]
6. Sustainability Research; Research from Henan University of Science and Technology Reveals New Findings on Sustainability Research. A Clean and Sustainable Cellulose-Based Composite Film Reinforced with Waste Plastic Polyethylene Terephthalate. *Ecol. Environ. Conserv.* **2020**, *2020*, 7323521.
7. Guo, W.; Guo, M.; Tan, Y.; Bai, E.; Zhao, G. Sustainable Development of Resources and the Environment: Mining-Induced Eco-Geological Environmental Damage and Mitigation Measures—A Case Study in the Henan Coal Mining Area, China. *Sustainability* **2019**, *11*, 4366. [CrossRef]
8. Jiao, L.; Deng, F.; Liang, X. Sustainable Urbanization Synergy Degree Measures—A Case Study in Henan Province, China. *Sustainability* **2017**, *10*, 9. [CrossRef]
9. Wu, C.; Gao, C. Study on the evaluation of the sustainability of mineral resources. *China Min.* **2007**, *16*, 24–27.
10. Gong, S.; Zhou, L.; Wang, W.; Wang, C. Investigation of dynamic fracture behavior and energy dissipation of water-bearing coal under impact load. *Eng. Fract. Mech.* **2022**, *275*, 108793. [CrossRef]
11. Qu, H.; Cao, X. Sustainable development and utilization of mineral resources in Henan Province. *J. Henan Univ. (Nat. Sci. Ed.)* **2000**, *30*, 88–91.
12. Bai, Y.; Hu, S. Study on the evaluation of the carrying capacity of mineral resources in Yantai City, Shandong Province. *Groundwater* **2020**, *42*, 136–139.
13. Dang, G.; Wu, C.; Wu, J. Study on the evaluation of the carrying capacity of national land resources in the mountainous areas of Longnan—Taking Liangdang County as an example. *Chin. Agron. Bull.* **2016**, *32*, 71–79.
14. Yan, Y.; Cheng, J. Evaluation of mineral resources carrying capacity of key mining economic zones. *Land Resour. Sci. Technol. Manag.* **2014**, *31*, 29–33.
15. Zhao, Z.; Peng, K. Research on the evaluation of sustainable development of mining cities: The case of Huaibei City. *Shanghai Land Resour.* **2014**, *35*, 39–42.
16. Wang, Z.; Zhu, Q.; Han, K. Preliminary discussion on the sustainable development of mineral resources in Henan. *Henan Prov. Stat.* **2001**, *4*, 9–10.
17. Xiong, Y.; Huang, C.; Ma, H. Evaluation of the economic carrying capacity of mineral resources in Henan: An analysis based on five major mineral resources. *China Min.* **2014**, *23*, 46–49.
18. Xue, L.; Cui, C.; Li, C. Regional mineral resource sustainability evaluation based on normal cloud model. *China Popul. Resour. Environ.* **2017**, *27*, 67–74.

19. Qin, J.; Liu, H.; Zhao, H.; Gu, F.; Jiang, D.; Zhu, Z.; Hou, J. Evaluation of ecological environment carrying capacity of mineral resources exploitation—Take Shenzhen as an example. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1087*, 012001. [CrossRef]
20. Li, C. Application of Fuzzy Recognition Method in Mineral Resources Allocation. *Sustain. Comput. Inform. Syst.* **2021**, *30*, 100509. [CrossRef]
21. Qiao, J. Analysis of Mineral Resources Security Factors Based on AHP Method. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2018; Volume 208.
22. Xue, L.; Su, C.; Cui, C.; Sun, Y. Application of the optimal combination assignment method under moment estimation theory to mineral resource evaluation. *China Min.* **2017**, *26*, 41–46.
23. Tang, Y.; Zhuo, Q.; Tou, Q.; Zhu, S.; Li, Y.; Zhao, Q.; Ding, Y. Evaluation and Countermeasures for Sustainable Development of Mineral Resources in Xiushan County. *J. Jishou Univ.* **2016**, *37*, 64–69.
24. Huang, H.; Yin, S.; Lei, Y. Analysis and prediction of sustainable development level of mineral resources in China–an exploration based on hierarchical analysis method. *J. Southwest Univ. Natl.* **2015**, *36*, 146–150.
25. Yu, J.; Gao, M. Comparative evaluation of the sustainability of mineral resources in mining cities. *Earth Sci.* **2007**, *32*, 123–129.
26. Wei, J. Analysis of the Competitiveness and Sustainability of the Bearing Capacity of Mineral Resources in Heilongjiang. *China Min.* **2006**, *15*, 102–106.
27. Yu, J. *Mineral Resource Sustainability Assessment*; China University of Geosciences Press: Beijing, China, 2017.
28. Yu, J.; Yao, S.-Z. Mineral Resource Sustainability and its System Construction. *Earth Sci. J. China Univ. Geosci.* **2002**, *25*, 85–89.
29. Li, Y.; Xiang, J. Application of Improved Entropy Method in Sustainability Evaluation of Mining Cities. *China Min.* **2009**, *18*, 45–48.
30. Yan, J.; Sun, Y. Analysis and measurement of mineral resources development index in Hebei Province. *J. Hebei Univ. Geosci.* **2022**, *45*, 90–96.
31. Gong, S. Investigation of tensile and fracture mechanical properties of bituminous coal at different strain rates. *J. Mater. Res. Technol.* **2021**, *15*, 834–845. [CrossRef]
32. Zhang, C.; Zhao, Y.; Bai, Q. 3D DEM method for compaction and breakage characteristics simulation of broken rock mass in goaf. *Acta Geotech.* **2022**, *17*, 2765–2781. [CrossRef]
33. Cun, Z.; Bo, L.; Ziyu, S.; Jinbao, L.; Jinlong, Z. Breakage mechanism and pore evolution characteristics of gangue materials under compression. *Acta Geotech.* **2022**, *17*, 4823–4835. [CrossRef]
34. Gong, S.; Wang, C.; Xi, F.; Jia, Y.; Zhou, L.; Zhang, H.; Wang, J.; Ren, X.; Wang, S.; Yao, S.; et al. Dynamic Tensile Mechanical Properties of Outburst Coal Considering Bedding Effect and Evolution Characteristics of Strain Energy Density. *Mathematics* **2022**, *10*, 4120. [CrossRef]
35. Huang, D.; Zheng, H. Scale-expansion construction method of judgment matrix in AHP method. *Syst. Eng.* **2003**, *21*, 1001–4098.
36. He, K. Scalar study of hierarchical analysis. *Syst. Eng. Theory Pract.* **1997**, *17*, 59–62.
37. Zhang, J. Singh. In *Information Entropy: Theory and Applications*; Beijing Water Resources and Hydropower Press: Beijing, China, 2012.
38. Wang, J.; Jiang, Y. Design and implementation of entropy-based fuzzy evaluation model for software quality. *Comput. Digit. Eng.* **2008**, *36*, 29–109.