



Research Article

Case Studies and Evaluation of Green Mining considering Uncertainty Factors and Multiple Indicator Weights

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Received 20 July 2020; Revised 12 August 2020; Accepted 31 August 2020; Published 12 October 2020

Academic Editor: Zhijie Wen

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The implementation of green mining (GM) can improve the quality of economic growth. Based on uncertainty measurement theory (UMT), we aim to develop a reasonable method of green mining (GM) evaluation for building material (BM) mines via comparative analysis. At first, establish UMT evaluating model for GM. The linear uncertainty (LU) measurement function was employed to solve single indicator measure values. Then, based on the entropy weight method (EWM), the analytic hierarchy process (AHP) and a method that couples AHP and EWM (EWM-AHP), and the weights of the evaluating indicator were determined. At last, based on UMT, a total of 6 coupled methods are developed to evaluate the GM grades. The GM grades of two building material mines in China were evaluated by applying the 6 methods. Future suggestions were given to the enterprises to improve the GM grades. According to the actual situations of GM in the two building material (BM) mines, it can be speculated that UMT-EWM-AHP-CDRT is the most reasonable method. The reasonable method can not only evaluate the GM grades for BM but also provide guidance to the development of GM for BM.

1. Introduction

The prosperity of a country's economy is inseparable from building material (BM) mines. The application of building material mineral resources is extensive. The rapid development of China's construction industry in the past 20 years is related to the support of building material mines. Building material enterprises have obtained substantial economic benefits. For instance, China National Building Material Group Co., Ltd achieved a net profit of more than 23 billion RMB in 2019 [1]. The largest cement producer in China-Hailuo Cement Group achieved a net profit of 23.816 billion RMB in the first three quarters of 2019 [2].

With economic development and extensive use of the building material mineral resources, building material mines have developed rapidly in China. Environmental pollution may be worse because of the increasing demand for building material mineral resources. The pollutants are mainly derived from crusher processing, soil erosion, and vegetation destruction [3, 4], which will cause environmental degradation. Furthermore, people's health will suffer considerably.

We should protect the environment while exploiting mineral resources from mines. Man and nature should live in harmony. Traditional exploitation of natural resources has been based mainly on the destruction of the natural environment and the loss of people's health [5–8]. And specially, the building material mining industry is characterized by “high pollution, high emissions, and high energy consumption” [9].

The implementation of green mining (GM) can improve the quality of economic growth. Mining companies have started adopting GM practices to help provide economic benefits while seeking minimal environmental damage. The United States government passed laws dictate that mining enterprises need to preserve soil for mining, and mines should be restored to their original condition after closure. In the process of mining development and utilization, if a mining company causes pollution to the environment, people may file a lawsuit with the court [10, 11]. The Australian government enforces mining enterprises by making plans for mine environmental protection and establishing a “mine closure fund” [12, 13]. The UK implemented a licensure system to prevent mineral resource exploitation, in which

licenses for relevant access management are issued by the government [14, 15]. The Chinese government has formulated detailed assessment conditions for GM, and mining enterprises that satisfy the requirements can receive corresponding tax exemptions [16]. Chile, Ghana, Finland, and other countries have all adopted relevant green mining measures [17–19].

Note that GM is a basic method for the sustainable development strategy of the mining industry [20, 21]. An evaluation of GM in the building material industry is important for improving the environmental quality of the whole country. Nevertheless, the traditional evaluation of GM is aimed mainly at metal mines [22, 23], gold mines [24], and coal mines [24, 25]. The research on GM grades for BM is extremely scarce, especially multiple uncertainty factors are considered comprehensively in the evaluation system. For example, Muduli et al. [26] discussed the establishment of a green mining evaluation system for coal mines by using the AHP, where detailed evaluating indicators were not listed. Simonov et al. [24] selected quantitative indicators to establish a basic evaluation model for coal mine based on fuzzy entropy theory, where GM grades were evaluated. Liu et al. [23] established an evaluating indicator system for Ghana's gold mine using GM with the AHP and fuzzy methodology.

These studies give some ideas that are worthy of consideration for the GM of BM. However, the selection of determining hierarchies and evaluating indicators in these studies is not appropriate enough, which can cause less accurate evaluation results. The determination of indicator weights depends on either expert experience or objective data. No comparison is available to confirm which one is better for GM. The determination of hierarchies and evaluation indicators relies on different evaluation models. Hence, it is of great practical significance to develop a reasonable method of GM evaluation for BM.

To reduce the effects of unreasonable hierarchies and indicators in the conventional evaluation methods for GM, the evaluating indicators were determined by investigating the pollutants and green ways and the engineering status of BM in this paper. Concentrating on the complicated and numerous evaluating indicators for GM of BM, the qualitative and quantitative indicators were combined to establish uncertainty measurement theory (UMT) evaluating models for GM. The linear uncertainty measurement function (LU)—an uncertainty mathematical method—was employed to establish the evaluation matrix [27–30]. In terms of determining the indicator weights, three methods were adopted for comparison, including a method that considers expert experience, a method that considers the objective data, and a combination of the two methods. (1) The Analytic hierarchy process (AHP) relies on expert experience and quantifies qualitative indicators. (2) The entropy weight method (EWM) is based on objective data and yields results that have strong objectivity but cannot reflect experts' personal experience. (3) The AHP-EWM combines the traits of AHP and EWM. Furthermore, credible degree recognition theory (CDRT) and Euclidean distance criteria (EDC) were employed to determine the grades of GM. A total of 6 evaluation methods, which were applied to two limestone mines in

China, were developed. Based on UMT, We aim to develop a reasonable method of GM evaluation for BM via comparative analysis.

2. Materials and Methods

2.1. Establishment of UMT Evaluating Indicator System. Many factors influence GM grades and involve many subjects. The Yirui limestone mine for construction in Anhui province, Xiazhang limestone mine for cement in Jiangxi province, Long Quan-wu sandstone mine for construction in Jiangsu province, and Hongtai quarry in Henan province, were investigated. Existing studies and expert opinions were employed, indicators with great relevance were deleted, and independent indicators were formed.

On the one hand, nineteen factors are selected as quantitative single evaluating indicators, including waste disposal ratio, greening ratio of functional area, cyclic utilization ratio of waste water, land reclamation ratio, operation noise, total suspended particulate (TSP) content, nitrogen oxide (NO_x) content, sulfur dioxide (SO_2) content, dichromate COD_{Cr} index, suspended solids (SS), pH value of water, casualties per million man hours, unit surrounding community investment, unit technical transformation investment, productivity of labor, unit fuel consumption, unit power consumption, recovery ratio, and dilution ratio, which are represented as X_{26} , X_{25} , X_{24} , X_{23} , X_{22} , X_{21} , X_{20} , X_{19} , X_{18} , X_{17} , X_{16} , X_8 , X_7 , X_6 , X_5 , X_4 , X_3 , X_2 , and X_1 , respectively.

On the other hand, 7 factors are selected as qualitative single evaluating indicators, including employee satisfaction ratio, digital mine level, functional area layout, environmental management system certification, quality management system certification enforcement of design parameters and measures, and environmental monitoring facility, which are represented as X_9 , X_{10} , X_{11} , X_{12} , X_{13} , X_{14} , and X_{15} , respectively. GM grades can be classified into 4 grades: A_1 , A_2 , A_3 , and A_4 .

A_1 represents the unqualified GM grade, A_2 represents the qualified GM grade, A_3 represents the good GM grade, and A_4 represents the excellent GM grade, respectively. The classification grades for the 7 qualitative indicators and 19 quantitative indicators are listed in Table 1.

2.2. Determination of the Single Indicator Measure Value. BM represents the building material mines to be evaluated. The single evaluating indicator space can be represented as $X = (X_1, X_2, \dots, X_{26})$, because the number of single evaluating indicator X is 26. $\text{BM} = (x_1, x_2, \dots, x_{26})$ can be a vector, and x_i is the measure value to the single evaluating indicator X_i . Likewise, (A_1, A_2, A_3, A_4) represents the space of GM grades for the BM. $A_k (k = 1, 2, 3, 4)$ represents the k th grade and is less advanced than the $(k + 1)$ th grade.

$\mu_{ij} = \mu(x_i \in A_k)$ represents the degree that the measure value x_i belongs to A_k , and μ denotes the single indicator measure value. Generally, the single indicator measure value is determined by the uncertainty measurement function.

However, no specified methods are available to select the uncertainty measurement functions, which are mostly selected based on subjective judgments and practical experience. After

TABLE 1: Evaluation grades of the qualitative indicators and quantitative indicators.

Single evaluating indicator	Unit	Evaluation grades			
		A_1	A_2	A_3	A_4
Dilution ratio (X_1)	%	8	6	4	2
Recovery ratio (X_2)	%	75	80	90	96
Unit power consumption (X_3)	kW.h/t	15	13	8	4
Unit fuel consumption (X_4)	kg/t	0.9	0.7	0.5	0.3
Productivity of labor (X_5)	10000-ton/person	0.5	1	3	5
Unit technical transformation investment (X_6)	USD/t	0.007	0.014	0.072	0.143
Unit surrounding community investment (X_7)	USD/t	0.01	0.016	0.1	0.15
Casualties per million man hours (X_8)	Person/mmh	20	15	10	5
Employee satisfaction ratio (X_9)		Poor	General	Good	Excellent
Digital mine level (X_{10})		Poor	General	Good	Excellent
Functional area layout (X_{11})		Poor	General	Good	Excellent
Environmental management system certification (X_{12})		Poor	General	Good	Excellent
Quality management system certification (X_{13})		Poor	General	Good	Excellent
Enforcement of design parameters and measures (X_{14})		Poor	General	Good	Excellent
Environmental monitoring facility (X_{15})		Poor	General	Good	Excellent
PH value of water (X_{16})		9.1	8.8	7.8	7.3
SS (X_{17})	mg/L	495	298	98	70
CODcr (X_{18})	mg/L	695	495	195	145
SO ₂ (X_{19})	mg/m ³	0.15	0.1	0.05	0.01
NO _x (X_{20})	mg/m ³	0.15	0.1	0.06	0.04
TSP (X_{21})	mg/m ³	0.4	0.26	0.18	0.06
Operation noise (X_{22})	dB	75	65	55	45
Land reclamation ratio (X_{23})	%	65	75	85	95
Cyclic utilization ratio of waste water (X_{24})	%	70	80	88	95
Greening ratio of functional area (X_{25})	%	20	30	45	50
Waste disposal ratio (X_{26})	%	80	85	90	95

the analysis and comparison, a linear uncertainty measurement function (LU) is applied to obtain the single indicator measure values.

- (1) The descending LU distribution is applied as the negative quantitative indicator, where the GM grade of BM decreases as the single evaluating indicator increases

$$\mu(x) = \begin{cases} \frac{-x}{a_{i+1} - a_i} + \frac{a_{i+1}}{a_{i+1} - a_i}, & a_i < x \leq a_{i+1}, \\ 0, & x > a_{i+1} \end{cases} \quad (1)$$

- (2) The rising LU distribution is applied as the positive quantitative indicator, where the GM grade of BM increases as the single evaluating indicator increases

$$\mu(x) = \begin{cases} \frac{x}{a_{i+1} - a_i} - \frac{a_i}{a_{i+1} - a_i}, & a_i < x \leq a_{i+1}, \\ 0, & x \leq a_i \end{cases} \quad (2)$$

where a_i denotes the lower limits of the value range and a_{i+1} denotes the upper limits of the value range.

LU uncertainty measurement functions for the 7 qualitative indicators and the 19 quantitative indicators are shown in Figure 1. After the single indicator measure values of the 26 evaluating indicators are calculated, the assessment matrix $(\mu_{ij})_{26 \times 4}$ of single indicator measure values can be obtained as follows:

$$(\mu_{ij})_{26 \times 4} = \begin{bmatrix} \mu_{11} & \mu_{12} & \cdots & \mu_{14} \\ \mu_{21} & \mu_{22} & \cdots & \mu_{24} \\ \vdots & \vdots & \ddots & \vdots \\ \mu_{261} & \mu_{262} & \cdots & \mu_{264} \end{bmatrix}. \quad (3)$$

2.3. Entropy Weight Method (EWM)

2.3.1. Determination of Evaluating Indicator Weight. Parameter v_i is the weight of the single evaluating indicator X_i . By

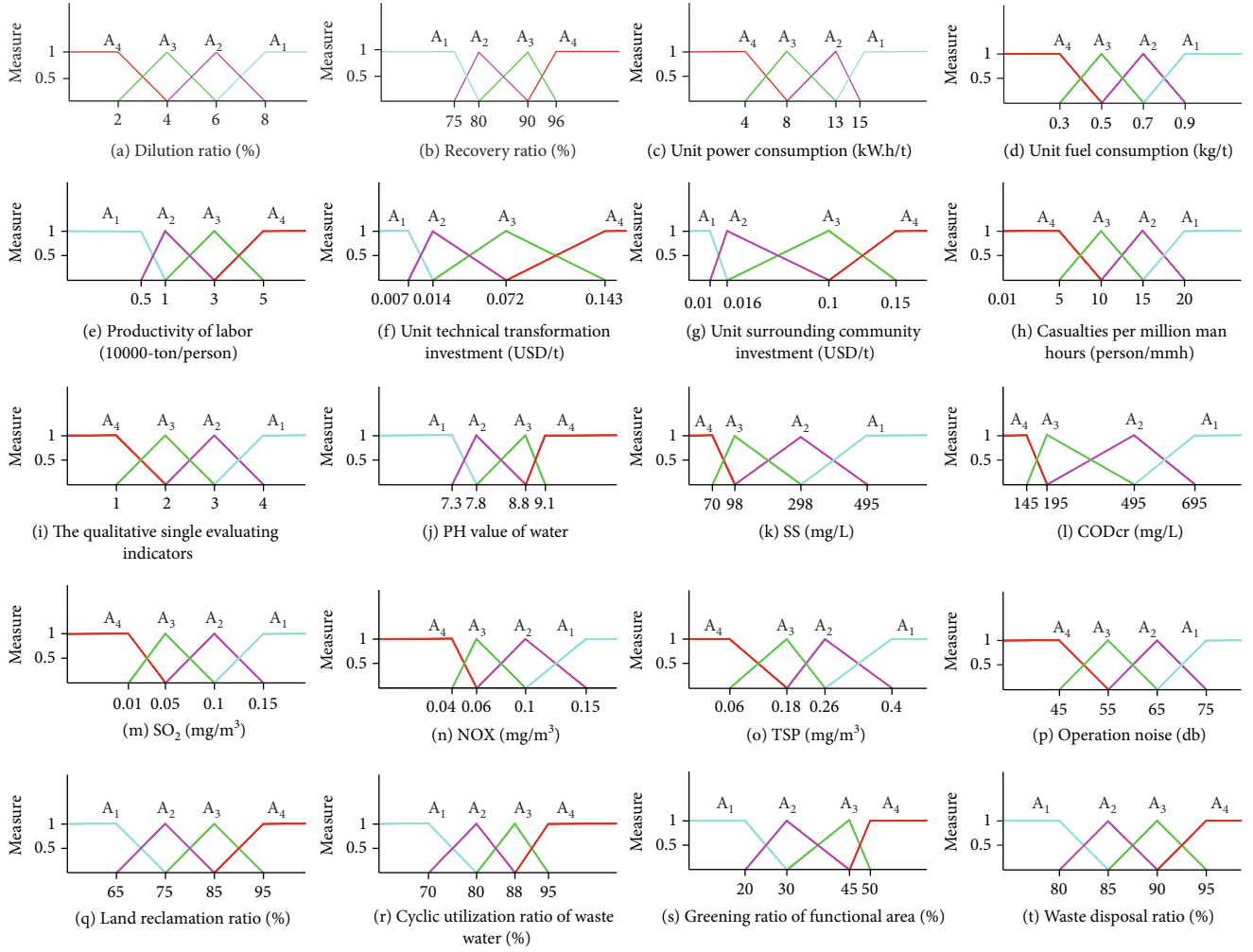


FIGURE 1: LU uncertainty measurement function for the 7 qualitative indicators and 19 quantitative indicators. The qualitative indicators have the same LU uncertainty measurement function, as shown in “(i).” The cyan line indicates the single indicator measure value of A_1 . The carmine line indicates the single indicator measure value of A_2 . The green line indicates the single indicator measure value of A_3 . The red line indicates the single indicator measure value of A_4 .

the entropy weight method, we can obtain the weight v_i as follows:

Step 1 (normalized matrix):

$$Y_{ij} = \frac{\mu_{ij} - \min(\mu_{ij})}{\max(\mu_{ij}) - \min(\mu_{ij})}. \quad (4)$$

Step 2 (entropy of the i th indicator is determined by (3)):

$$E_i = -\ln(4)^{-1} \sum_{j=1}^4 p_{ij} \ln p_{ij}, \quad (5)$$

where

$$p_{ij} = \frac{Y_{ij}}{\sum_{j=1}^4 Y_{ij}} \quad (6)$$

Step 3 (calculation of the indicator's entropy weight):

$$v_i = \frac{1 - E_i}{26 - \sum E_i}. \quad (7)$$

2.3.2. *Comprehensive Evaluation Vector in the EWM.* $\rho_k = \rho(\text{BM} \in A_k)$ represents the degree that the BM belongs to A_k , which is given by

$$\rho_k = \sum_{i=1}^{26} v_i \mu_{ij}(k = 1, 2, 3, 4). \quad (8)$$

$\sum_{k=1}^4 \rho_k = 1$ and $0 \leq \rho_k \leq 1$ need to be satisfied here. Thus, the comprehensive evaluation vector is $(\rho_1, \rho_2, \rho_3, \rho_4)$ in EWM theory for the BM.

TABLE 2: AHP model for GM grades of BM.

Target (T)	Criteria (M)	Indicator factor (X)
GM grades A_k	Mining control level (M_1)	Dilution ratio (X_1)
		Recovery ratio (X_2)
	Mining energy savings (M_2)	Unit power consumption (X_3)
		Unit fuel consumption (X_4)
		Productivity of labor (X_5)
	Addition items (M_3)	Unit technical transformation investment (X_6)
		Unit surrounding community investment (X_7)
		Casualties per million man hours (X_8)
		Employee satisfaction ratio (X_9)
		Digital mine level (X_{10})
	Comprehensive management level (M_4)	Functional area layout (X_{11})
		Environmental management system certification (X_{12})
		Quality management system certification (X_{13})
		Enforcement of design parameters and measures (X_{14})
		Environmental monitoring facility (X_{15})
	Comprehensive environmental level (M_5)	pH value of water (X_{16})
		SS (X_{17})
		CODcr (X_{18})
		SO ₂ (X_{19})
		NOx (X_{20})
		TSP (X_{21})
		Operation noise (X_{22})
		Land reclamation ratio (X_{23})
		Cyclic utilization ratio of waste water (X_{24})
		Greening ratio of functional area (X_{25})
	Environmental restoration (M_6)	Waste disposal ratio (X_{26})

2.4. Analytic Hierarchy Process (AHP) Method

2.4.1. *Establishment of Hierarchical Model.* The model consists of the target hierarchy, criteria hierarchy, and indicator factor hierarchy. In general, the target hierarchy T is the problem that needs to be solved and means the GM grade A_k for BM.

The criteria hierarchy M is determined by the analysis of the specific problem. The evaluation of GM is a comprehensive subject, including the mining control level, mining energy savings, addition items, comprehensive management level, comprehensive environmental level, and environmental restoration in the criteria hierarchy M . The indicator factor hierarchy consists of 26 single evaluating indicators, which is the result of the decomposition of the criteria hierarchy M . The AHP model consists of 1 target, 6 criterion, and 26 indicator factors, which are detailed in Table 2.

2.4.2. *Establishment and Verification of the Judgment Matrix.* The 1–9 scale method is applied to establish the judgment matrix. For example, it is assumed that M denotes the importance degree in the criteria hierarchy, which is the value of M_a with respect to M_b . The rules are shown in Table 3.

According to the comparison, the judgment matrix T can be obtained as follows:

$$T_{6 \times 6} = \begin{bmatrix} t_{11} & t_{12} & \cdots & t_{16} \\ t_{21} & t_{22} & \cdots & t_{26} \\ \vdots & \vdots & \ddots & \vdots \\ t_{61} & t_{62} & \cdots & t_{66} \end{bmatrix}. \quad (9)$$

The maximum eigenvalue λ_{\max} and the eigenvector $\sigma_T = (\sigma_1, \sigma_2, \sigma_3, \sigma_4, \sigma_5, \sigma_6)$ of matrix T can be obtained. Likewise, the corresponding eigenvectors, judgment matrixes, and maximum eigenvalues of $M_1, M_2, M_3, M_4, M_5,$ and M_6 can be obtained.

All the judgment matrixes need to be verified. The consistency index CI is calculated by (10). Refer to Table 4 to obtain the value of the average random consistency index (RCI). Therefore, calculating the value of the consistency ratio (CR) by (11). The judgment matrix consistency is qualified

TABLE 3: Importance between criteria M_a and criteria M_b (modified from Jiang et al. [31]).

Definition	Numerical value
a, b elements are “equally important”	1
a element is “slightly more important” than b element	3
a element is “obviously more important” than b element	5
a element is “intensely more important” than b element	7
a element is “extremely more important” than b element	9
a element is “slightly less important” than b element	1/3
a element is “obviously less important” than b element	1/5
a element is “intensely less important” than b element	1/7
a element is “extremely less important” than b element	1/9
Importance degree is between the previous two values	2, 4, 6, 8, 1/2, 1/4, 1/6, 1/8

TABLE 4: RCI values.

n	1	2	3	4	5	6	7	8	9
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

when $CR < 0.1$ is satisfied; if not, the judgment matrix needs to be rebuilt.

$$CI = \frac{\lambda_{\max} - n}{n - 1}, \quad (10)$$

where n denotes the row number of the judgment matrix.

$$CR = \frac{CI}{RCI}. \quad (11)$$

2.4.3. Calculation of the Indicator Weight. The results of the judgment matrixes and corresponding eigenvectors of $M_1, M_2, M_3, M_4, M_5,$ and M_6 are shown in (12-18). The results of the maximum eigenvalues and consistency verifications of $M_1, M_2, M_3, M_4, M_5,$ and M_6 are shown in Table 5. Obviously, $CR < 0.10$ is satisfied for all the judgment matrixes. Therefore, all the matrixes are qualified. According to the eigenvectors, the weights of the indicator factor hierarchy (V_i) are obtained. Table 6 lists the weights of every hierarchy.

$$T_{6 \times 6} = \begin{bmatrix} 1 & 1/3 & 1 & 1/7 & 1/7 & 1/7 \\ 3 & 1 & 1/3 & 1/3 & 1/5 & 1/5 \\ 1 & 3 & 1 & 1/5 & 1/5 & 1/5 \\ 7 & 3 & 5 & 1 & 1 & 1 \\ 7 & 5 & 5 & 1 & 1 & 1/3 \\ 7 & 5 & 5 & 1 & 3 & 1 \end{bmatrix}$$

TABLE 5: λ_{\max} and CR of judgment matrixes.

Judgment matrixes	λ_{\max}	CR
$T_{6 \times 6}$	6.5057	0.0816(<0.1)
M_1	2.0000	0.0000(<0.1)
M_2	2.0000	0.0000(<0.1)
M_3	4.1725	0.0599(<0.1)
M_4	7.7594	0.0959(<0.1)
M_5	7.0000	0.0000(<0.1)
M_6	4.0104	0.0036(<0.1)

TABLE 6: Weights of every hierarchy in the AHP model.

Target (T)	Criteria (M)	Indicator factor (X)
		$X_1 = 0.01914$
	$M_1 = 0.03828$	$X_2 = 0.01914$
		$X_3 = 0.03238$
	$M_2 = 0.06477$	$X_4 = 0.03238$
		$X_5 = 0.01437$
		$X_6 = 0.01316$
	$M_3 = 0.07154$	$X_7 = 0.00767$
		$X_8 = 0.03635$
		$X_9 = 0.02229$
		$X_{10} = 0.01331$
		$X_{11} = 0.01514$
	$M_4 = 0.25515$	$X_{12} = 0.06134$
		$X_{13} = 0.07023$
		$X_{14} = 0.04261$
		$X_{15} = 0.03023$
		$X_{16} = 0.03722$
		$X_{17} = 0.03722$
		$X_{18} = 0.03722$
	$M_5 = 0.23575$	$X_{19} = 0.03722$
		$X_{20} = 0.03722$
		$X_{21} = 0.03722$
		$X_{22} = 0.01241$
		$X_{23} = 0.15961$
	$M_6 = 0.33452$	$X_{24} = 0.04289$
		$X_{25} = 0.04623$
		$X_{26} = 0.08578$

$$\sigma_T = (0.03828, 0.06477, 0.07154, 0.25515, 0.23575, 0.33452)^T$$

$$M_1 = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$$

$$\sigma_{M_1} = (0.5, 0.5)^T$$

$$M_2 = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$$

$$\sigma_{M_2} = (0.5, 0.5)^T$$

$$M_3 = \begin{bmatrix} 1 & 1 & 3 & 1/4 \\ 1 & 1 & 2 & 1/3 \\ 1/3 & 1/2 & 1 & 1/3 \\ 4 & 3 & 3 & 1 \end{bmatrix}$$

$$\sigma_{M_3} = (0.20087, 0.18396, 0.10714, 0.50803)^T$$

$$M_4 = \begin{bmatrix} 1 & 4 & 3 & 1/5 & 1/5 & 1/5 & 1/4 \\ 1/4 & 1 & 1 & 1/4 & 1/4 & 1/3 & 1/2 \\ 1/3 & 1 & 1 & 1/3 & 1/3 & 1/3 & 1/2 \\ 5 & 4 & 3 & 1 & 1 & 2 & 2 \\ 5 & 4 & 3 & 1 & 1 & 3 & 3 \\ 5 & 3 & 3 & 1/2 & 1/3 & 1 & 2 \\ 4 & 2 & 2 & 1/2 & 1/3 & 1/2 & 1 \end{bmatrix}$$

$$\sigma_{M_4} = (0.08737, 0.05216, 0.05934, 0.24040, 0.27524, 0.16701, 0.11848)^T$$

$$M_5 = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 3 \\ 1 & 1 & 1 & 1 & 1 & 1 & 3 \\ 1 & 1 & 1 & 1 & 1 & 1 & 3 \\ 1 & 1 & 1 & 1 & 1 & 1 & 3 \\ 1 & 1 & 1 & 1 & 1 & 1 & 3 \\ 1 & 1 & 1 & 1 & 1 & 1 & 3 \\ 1/3 & 1/3 & 1/3 & 1/3 & 1/3 & 1/3 & 1 \end{bmatrix}$$

$$\sigma_{M_5} = (0.15789, 0.15789, 0.15789, 0.15789, 0.15789, 0.15789, 0.05263)^T$$

$$M_6 = \begin{bmatrix} 1 & 4 & 3 & 2 \\ 1/4 & 1 & 1 & 1/2 \\ 1/3 & 1 & 1 & 1/2 \\ 1/2 & 2 & 2 & 1 \end{bmatrix}$$

$$\sigma_{M_6} = (0.47714, 0.12821, 0.13821, 0.25643)^T. \quad (12)$$

2.4.4. *Comprehensive Evaluation Vector in AHP.* $\eta_k = \eta(\text{BM} \in A_k)$ represents the degree that the BM belongs to A_k . The assessment matrix $(\mu_{ij})_{26 \times 4}$ and indicator factor weights are obtained, and the comprehensive evaluation

vector $(\eta_1, \eta_2, \eta_3, \eta_4)$ can be determined in the same way as that of EWM theory, which is shown as follows:

$$\eta_k = \sum_{i=1}^{26} V_i \mu_{ij} (k = 1, 2, 3, 4). \quad (13)$$

2.5. EWM-AHP Method

2.5.1. *Determination of Evaluating Indicator Weight.* According to AHP and EWM coupling in principle, Equation (14) can be applied to obtain the integrated weight value h_i as follows:

$$h_i = \frac{v_i V_i}{\sum_{i=1}^{26} (v_i V_i)}. \quad (14)$$

2.5.2. *Comprehensive Evaluation Vector in EWM-AHP.* In the same way, $\tau_k = \tau(\text{BM} \in A_k)$ represents the degree that BM belongs to A_k . The comprehensive evaluation vector $(\tau_1, \tau_2, \tau_3, \tau_4)$ can be determined in the same way as that of EWM theory, which is shown as follows:

$$\tau_k = \sum_{i=1}^{26} V_i \mu_{ij} (k = 1, 2, 3, 4). \quad (15)$$

2.6. *Recognition Criteria for EWM, AHP, and EWM-AHP.* To ensure that the evaluation results for BM are reasonable and reliable, CDRT and EDC are applied to determine the cleaner production grades, compare the evaluation results, and verify the reasonability.

(1) Credible degree recognition theory (CDRT)

It is assumed that $\psi (\psi \geq 0.5)$ represents the credible degree. Considering the comprehensive evaluation vector $(\rho_1, \rho_2, \rho_3, \rho_4)$ as an example, it is believable that BM belongs to A_k when (16) and (17) are satisfied.

$$k = \min \left(k : \sum_{j=1}^k \gamma_j \geq \psi, 1 \leq k \leq 4 \right), \quad (16)$$

where the comprehensive evaluation vector $(\rho_1, \rho_2, \rho_3, \rho_4)$ is arranged from small to large.

$$k = \min \left(k : \sum_{j=1}^k \gamma_j \geq \psi, 1 \leq k \leq 4 \right), \quad (17)$$

where the comprehensive evaluation vector $(\rho_1, \rho_2, \rho_3, \rho_4)$ is arranged from large to small.

(2) Euclidean distance criteria (EDC)

The Euclidean distance is also referred to as the Euclidean metric [32]. Similarly, considering the comprehensive evaluation vector $(\rho_1, \rho_2, \rho_3, \rho_4)$ as

an example, Equation (18) can be employed to obtain the Euclidean distance value d_i as follows:

$$\left\{ \begin{array}{l} d_1 = \sqrt{(\rho_1 - 1)^2 + (\rho_2 - 1)^2 + (\rho_3 - 0)^2 + (\rho_4 - 0)^2} \\ d_2 = \sqrt{(\rho_1 - 0)^2 + (\rho_2 - 1)^2 + (\rho_3 - 0)^2 + (\rho_4 - 0)^2} \\ d_3 = \sqrt{(\rho_1 - 0)^2 + (\rho_2 - 0)^2 + (\rho_3 - 1)^2 + (\rho_4 - 0)^2} \\ d_4 = \sqrt{(\rho_1 - 0)^2 + (\rho_2 - 0)^2 + (\rho_3 - 0)^2 + (\rho_4 - 1)^2} \end{array} \right. \quad (18)$$

It is confirmed that the BM belongs to A_k when (19) is satisfied.

$$k = \min d_i (1 \leq i \leq 4). \quad (19)$$

2.7. Evaluation Process of GM Grade for the BM. After the selection of the LU uncertainty measurement function of UMT, the single indicator measure values for 26 evaluating indicators can be determined quantitatively.

It is easy to obtain the evaluating matrix $(\mu_{ij})_{26 \times 4}$ solved by the LU uncertainty measurement function. The weights of single evaluating indicators are solved by *EWM*, *AHP*, and *EWM-AHP*, respectively. Therefore, the comprehensive evaluating vectors, including *UMT-EWM*, *UMT-AHP*, and *UMT-EWM-AHP*, are obtained.

The recognition criteria CDRT and EDC are applied to evaluate the GM grades. A total of 6 coupled methods, including *UMT-EWM-CDRT*, *UMT-AHP-CDRT*, *UMT-EWM-AHP-CDRT*, *UMT-EWM-EDC*, *UMT-AHP-EDC*, and *UMT-EWM-AHP-EDC* are developed to evaluate the GM grade. The evaluation process for the GM grade of the BM is shown in Figure 2.

3. Case Studies

Anhui province is a major province of mineral resources in China. By the end of 2018, 810 noncoal mines existed in Anhui province; 365 (45.06%) were building material mines (from the government work report of Anhui province [33]). Two building material mines from Anhui province were chosen as cases in this paper.

3.1. Yirui Limestone Mine. The Yirui limestone mine is located in Dongzhi County, Anhui Province, on the south bank of the Yangtze River. The hardness of fresh ore is between grade 8 and grade 12, and the uniaxial compressive strength of fresh ore is between 120 Mpa and 140 Mpa, which satisfies the requirements of the building stone utilized in construction and demonstrates reasonable quality. The ore body is exposed on the surface, and only part of the area is covered by the Quaternary strata. After blasting in a stope, the ore is shoveled by a hydraulic excavator and transported by truck to a stationary crushing station. After the ore is crushed and screened in the crushing station, different size stones are produced via different discharge ports.

There are 19 quantitative single evaluating indicators and 7 qualitative single evaluating indicators in the evaluating indicator system. The actual measure values of the 26 single evaluating indicators for the Yirui limestone mine are listed in Table 7. The assessment matrix of the single indicator measure value $(\mu_{ij})_{26 \times 4}$ for the Yirui limestone mine can be obtained in Table 8.

The Delphi method [34] was employed to obtain the measure values of 7 qualitative single evaluating indicators. The expert group consists of 6 university professors, 10 senior engineers from other limestone mines, and 3 managers from government departments. Among these 19 experts are 5 mining engineers, 2 geological engineers, 5 environmental protection engineers, 5 soil and water conservation engineers, and 2 related technical engineers. After three rounds of grading, the experts formed a consensus.

The values of the 19 quantitative evaluating indicators can be obtained by measurement and calculation. For example, the indicators value of the comprehensive environmental level criteria M_5 , which contains $X_{16} - X_{22}$, can be obtained by daily monitoring measurement. The indicator value of environmental restoration M_6 , which contains $X_{23} - X_{26}$, can be obtained by measurement and then calculation. Note that $X_1, X_2, X_6, X_8, X_{24}$, and X_{26} are all evaluated as A4. Satisfactory geological conditions of ore occurrence, a small amount of soil and undeveloped karst have an important role in the aspect of X_1 and X_2 .

The crushing process in a traditional crushing station is exposed to the outdoors. The noise is loud, and the flying dust is everywhere. In recent years, the Yirui mine has upgraded the crushing station to reduce dust and noise. The crushing station is sealed with colored steel tiles. The crusher and vibrating screen are equipped with four bag-type dust collectors, and the finished ore is stored separately by categories. The plant adopts water spray mist to reduce dust in the workshop. These aspects produce a high grade for X_6 .

The mining industry is a high-risk industry. The Yirui mine always prioritizes safety production and formulates postoperation rules and emergency plans. Furthermore, implement reward or punishment measures when necessary. At this point, it is reasonable that X_8 has a high grade.

There are five sedimentation tanks, one clean water basin and corresponding drainage ditches around the crushing station. Rainwater and sewage are filtered into the clean water basin after precipitation. The pond is the water supply point of the sprinkler and spray mist. The waste water returns to the sedimentation tank so that the waste water can be recycled. Therefore, X_{24} is evaluated as A_4 . For X_{26} , the striping soil in mining can be used to restore the stope vegetation in time, which can reduce the land pressure and improve the waste disposal ratio.

The weights of the evaluating indicators are listed in Table 9. The weights for the *EWM-AHP* method are arranged from large to small, with X_{26} (waste disposal ratio), X_{23} (and reclamation ratio), X_{24} (cyclic utilization ratio of waste water), X_8 (casualties per million man hours), and X_{13} (quality management system certification) in the top five

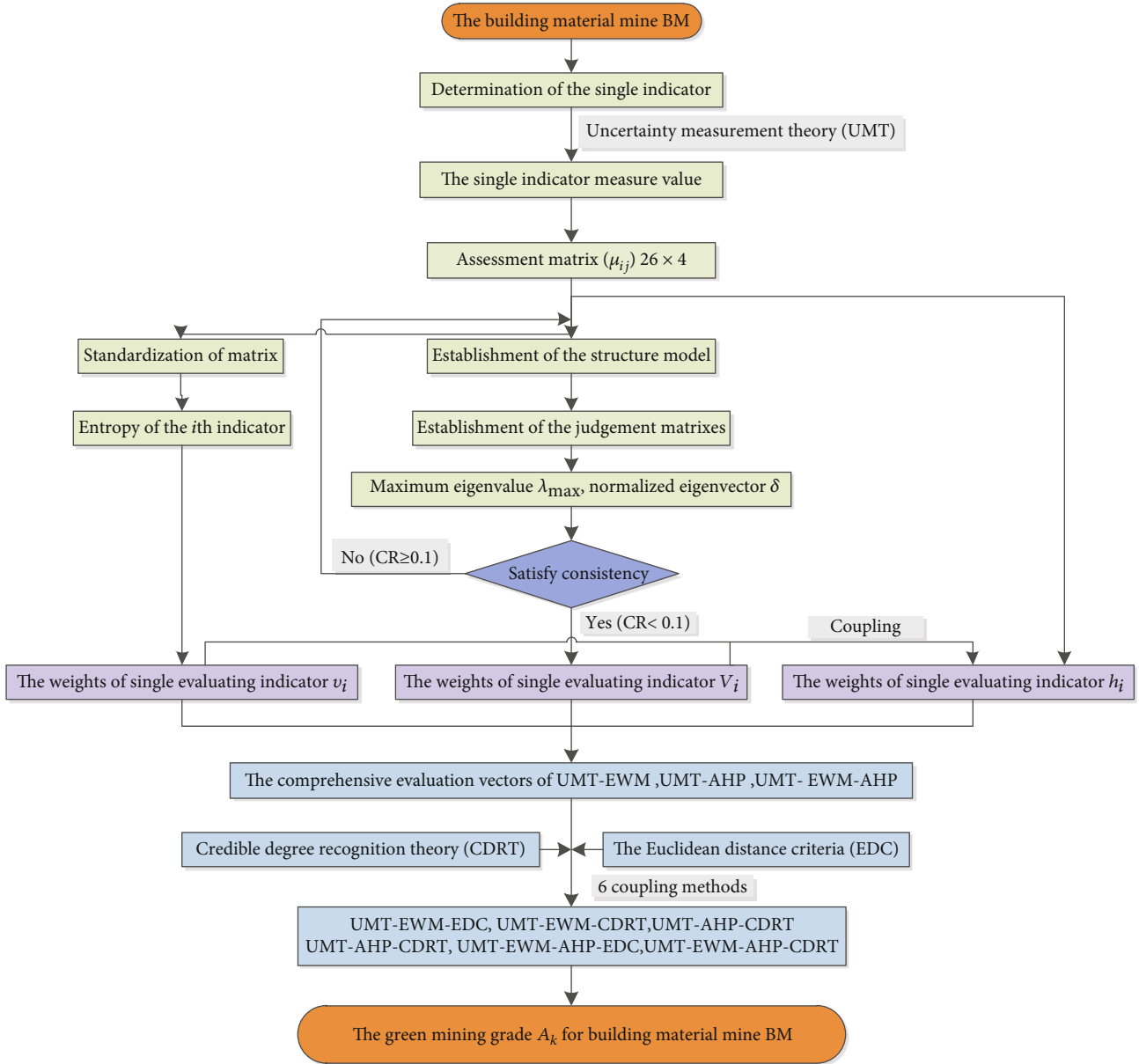


FIGURE 2: Flowchart for evaluating GM grade A_k of the BM.

weights and X_9 (employee satisfaction ratio), X_{10} (digital mine level), X_5 (productivity of labor), X_{22} (operation noise), and X_7 (unit surrounding community investment) in the last five weights. The weights of the bottom five evaluating indicators add up to less than half of the maximum weight indicator X_{26} ($0.05768 < 0.13524/2$).

The greater is the weight value, the greater is the impact on the evaluation level of GM. Obviously, the indicator with the greatest influence on the evaluation grade of GM is X_{26} , and the indicator with the least influence is X_7 . The evaluation grades of GM can be obtained by combining evaluating indicator weights and the recognition criteria for EWM, AHP, and EWM-AHP, as shown in Table 10. The GM grades of Yirui limestone mine without one exception is rated as A_4 , based on six evaluation methods.

The evaluating indicators that ranked in the top five with weight values are all evaluated as having high grades, as shown in Table 8. Therefore, it is confirmed that the reason that Yirui limestone mine is rated as A_4 by all the six methods is that the indicator factors that ranked in the top five all performed very well. The sum of the weights of the top five evaluating indicators is 0.44133, which is near 0.5.

3.2. Mingguang Limestone Mine. The Mingguang limestone mine is located in Xuancheng city, Anhui province. The ore quality is consistent with the general requirements of building stone. The surface soil is thick, karst is developed, and 5 large faults are distributed in the mining area. Therefore, the occurrence condition of the ore body is poor, which directly yields a high dilution ratio. The Mingguang

TABLE 7: Actual measure values of the 26 single evaluating indicators for Yirui limestone mine and Mingguang limestone mine.

Evaluating indicator	Measure value		Evaluating indicator	Measure value	
	Yirui mine	Mingguang mine		Yirui mine	Mingguang mine
X_1	1.5	3	X_{14}	2.5	3
X_2	98	97	X_{15}	1.5	3
X_3	6	14	X_{16}	7.5	8.8
X_4	0.45	0.6	X_{17}	80	135
X_5	4	6	X_{18}	175	265
X_6	0.2	0.009	X_{19}	0.03	0.12
X_7	0.12	0.17	X_{20}	0.05	0.11
X_8	0	21	X_{21}	0.09	0.31
X_9	2.5	2	X_{22}	50	60
X_{10}	2.5	4	X_{23}	90	45
X_{11}	2	3	X_{24}	96	75
X_{12}	1.5	3	X_{25}	46	46
X_{13}	1.5	3	X_{26}	96	75

limestone mine adopts the same mining technology and crushing processing as the Yirui limestone mine but the crusher has a long service time and is experiencing considerable aging. The enterprise environmental protection consciousness is weak, although the crushing station is simply closed; however, neither a dust collector nor spray facilities are not installed. The mine built new rural roads for the surrounding communities, donated a primary school, and absorbed the employment of the surrounding villagers. Production management is chaotic, employees often work overtime, and sometimes employees are injured on the job.

In the same way, the actual measure values of the 26 single evaluating indicators for the Mingguang limestone mine are shown in Table 7, and the assessment matrix of the single indicator measure values $(\mu_{ij})_{26 \times 4}$ for the Mingguang limestone mine is shown in Table 8.

Similarly, the Delphi method [34] was employed to obtain the measure values of qualitative single evaluating indicators, and the measurement and calculation are employed to obtain the values of the quantitative evaluating indicators. Note that X_{10} , X_{23} , X_{26} are all evaluated as A_1 . The Mingguang limestone mine installed surveillance cameras at key locations and set up monitoring rooms. However, the enterprise and the related technical engineers do not have the digital software. Furthermore, many lands have stacked debris but are not used for reclamation. The slopes that are not mined have not been reclaimed. Due to the thick surface soil and acquisition difficulties for the surrounding land, the enterprise piles up the soil in the stope.

As shown in Table 11, the weights of the evaluating indicators are listed. The weights for the *EWM-AHP* method are arranged from large to small, with X_{23} (land reclamation ratio), X_{26} (waste disposal ratio), X_{13} (quality management system certification), X_{12} (environmental management system certification), X_{14} (enforcement of design parameters and measures) in the top five weights, and X_{10} (digital mine level), X_1 (dilution ratio), X_7 (unit surrounding community

investment), X_6 (unit technical transformation investment), and X_{22} (operation noise) in the last five weights.

The weights of the bottom five evaluating indicators comprise less than one-third of the maximum weight indicator X_{26} ($0.05318 < 0.19194/3$). Similarly, we can reach the conclusion that the greater is the weight value, the greater is impact on the evaluation level of GM. Obviously, the indicators with the greatest influence on the evaluation grade of GM are the group of the top five indicators, and the indicators with the least influence are the group of the last five indicators. However, the group of the middle 16 indicators have moderate influence on the evaluation grade of GM, which are X_{16} , X_8 , X_{15} , X_{25} , X_{27} , X_{20} , X_{18} , X_9 , X_{24} , X_{21} , X_{19} , X_2 , X_4 , X_3 , X_{11} , X_5 , respectively.

If the enterprise wants to change the grade of GM, it is important to focus on improving the top five indicators. Table 12 lists the evaluation grades of GM for the Mingguang limestone mine. The evaluation grade of GM is A_1 to UMT-EWM-CDRT, UMT-AHP-CDRT, and UMT-EWM-AHP-CDRT. However, the evaluation grade of GM is A_2 to UMT-EWM-EDC, UMT-AHP-EDC, and UMT-EWM-AHP-EDC.

3.3. Future Suggestions. It is feasible to give some suggestions to the enterprises, via Sections 3.1 and 3.2. The Yirui limestone mine has performed excellent work in GM. The suggestions focus on the Mingguang limestone mine, combined with Tables 11 and 12. The weights of the evaluating indicators are arranged in order from small to large with the *EWM-AHP* method, with X_{23} , X_{26} , X_{13} , X_{12} , X_{14} in the top five. The weights of the top five evaluating indicators add to $0.50454 > 0.5$.

It can be suggested that the five indicators have a crucial role in the grade of GM. In particular, the land reclamation ratio (X_{23}) and waste disposal ratio (X_{26}) are rated as A_1 . Quality management system certification (X_{13}), environmental management system certification (X_{12}), and

TABLE 8: Assessment matrixes of single indicator measure values for Yirui limestone mine and Mingguang limestone mine.

Evaluating indicator	Yirui mine				Mingguang mine			
	A_1	A_2	A_3	A_4	A_1	A_2	A_3	A_4
X_1	0	0	0	1	0	0	0.5	0.5
X_2	0	0	0	1	0	0	0	1
X_3	0	0	0.5	0.5	0.5	0.5	0	0
X_4	0	0	0.75	0.25	0	0.5	0.5	0
X_5	0	0	0.5	0.5	0	0	0	1
X_6	0	0	0	1	0.7143	0.2857	0	0
X_7	0	0	0.6	0.4	0	0	0	1
X_8	0	0	0	1	0	0	0	1
X_9	0	0.5	0.5	0	0	0	1	0
X_{10}	0	0.5	0.5	0	1	0	0	0
X_{11}	0	0	1	0	0	1	0	0
X_{12}	0	0	0.5	0.5	0	1	0	0
X_{13}	0	0	0.5	0.5	0	1	0	0
X_{14}	0	0.5	0.5	0	0	1	0	0
X_{15}	0	0	0.5	0.5	0	1	0	0
X_{16}	0	0	0.4	0.6	0	1	0	0
X_{17}	0	0	0.3571	0.6429	0	0.185	0.815	0
X_{18}	0	0	0.6	0.4	0	0.2333	0.7667	0
X_{19}	0	0	0.5	0.5	0.4	0.6	0	0
X_{20}	0	0	0.5	0.5	0.2	0.8	0	0
X_{21}	0	0	0.25	0.75	0.3571	0.6429	0	0
X_{22}	0	0	0.5	0.5	0	0.5	0.5	0
X_{23}	0	0	0.5	0.5	1	0	0	0
X_{24}	0	0	0	1	0.5	0.5	0	0
X_{25}	0	0	0.8	0.2	0	0	0.8	0.2
X_{26}	0	0	0	1	1	0	0	0

enforcement of design parameters and measures (X_{14}) are not high enough and are rated as A_2 .

Measures should be taken to give priority to improve the indicators with high weights and low grades in Table 8 and then further improve only the indicators with high weights to improve the grade of GM.

Therefore, X_{23} and X_{26} should be improved first. The Mingguang limestone mine should learn from the Yirui limestone mine. The stripping soil in mining can be employed for reclamation of slope in time, which can reduce the land pressure and improve the waste disposal ratio. In addition, soil can be utilized for new roads, landscaping, and housing. Lands with stacked debris should be cleared and then planted with vegetation. X_{13} , X_{12} , and X_{14} are qualitative indicators; to improve them, corresponding rules and regulations are necessary with the responsibility placed on the individual.

For example, formulate the postoperation rules and conduct safety education for employees. The construction contract shall specify that mining shall be carried out in

accordance with the design parameters, failing which the corresponding penalty shall be imposed. Some engineering measures can be taken, similar to the Yirui limestone. Update crushing equipment, install a dust collector, and spray equipment. Construct sedimentation tanks and clean the water basin and corresponding drainage ditches; clean them regularly to improve the recycling system of waste water. After the construction of environmental protection facilities, the corresponding evaluation indicators can be improved, such as X_{13} , X_{12} , X_{16} , and X_{15} .

3.4. Results and Discussions. A total of 6 coupled methods, including UMT-EWM-CDRT, UMT-AHP-CDRT, UMT-EWM-AHP-CDRT, UMT-EWM-EDC, UMT-AHP-EDC, and UMT-EWM-AHP-EDC, are developed to evaluate the GM grade. The results of GM grades for the two mines are shown in Table 13. The GM grades of the Yirui limestone mine are rated as A_4 via six evaluation methods. For the Mingguang limestone mine, the GM grades are rated as A_1 or A_2 which depends on different evaluation methods.

TABLE 9: Weights of evaluating indicators for Yirui limestone mine. The underlined values indicate the smallest five evaluating indicator weights with the EWM-AHP method. The bold values indicate the largest five evaluating indicator weights with the EWM-AHP method.

Evaluating indicator	EWM	Weight AHP	EWM-AHP	Evaluating indicator	EWM	Weight AHP	EWM-AHP
X_1	0.05874	0.01914	0.03018	X_{14}	0.03177	0.04261	0.03633
X_2	0.05874	0.01914	0.03018	X_{15}	0.02937	0.03023	0.02383
X_3	0.02937	0.03238	0.02553	X_{16}	0.03022	0.03722	0.03019
X_4	0.03491	0.03238	0.03034	X_{17}	0.03113	0.03722	0.03110
X_5	0.02937	0.01437	<u>0.01133</u>	X_{18}	0.03022	0.03722	0.03019
X_6	0.05874	0.01316	0.02075	X_{19}	0.02937	0.03722	0.02934
X_7	0.03022	0.00767	<u>0.00622</u>	X_{20}	0.02937	0.03722	0.02934
X_8	0.05874	0.03635	0.05730	X_{21}	0.03491	0.03722	0.03488
X_9	0.03177	0.02229	<u>0.01901</u>	X_{22}	0.02937	0.01241	<u>0.00978</u>
X_{10}	0.03177	0.01331	<u>0.01135</u>	X_{23}	0.02937	0.15961	0.12582
X_{11}	0.05874	0.01514	0.02387	X_{24}	0.05874	0.04289	0.06762
X_{12}	0.02937	0.06134	0.04835	X_{25}	0.03754	0.04623	0.04658
X_{13}	0.02937	0.07023	0.05536	X_{26}	0.05874	0.08578	0.13524

TABLE 10: Comprehensive evaluation vectors, Euclidean distances, credible degree recognitions, and GM grades for Yirui limestone mine.

Method	Comprehensive evaluation vector	Euclidean distance (d_i)	Credible degree recognition	GM grade
UMT-EWM-CDRT	(0.00000,0.04766,0.36298,0.58936)		$\rho_1 + \rho_2 + \rho_3 + \rho_4 = 1.0 > 0.5$, $\rho_4 = 0.58936 > 0.5$	A_4
UMT-EWM-EDC	(0.00000,0.04766,0.36298,0.58936)	1.2171,1.1773,0.8691,0.5501		A_4
UMT-AHP-CDRT	(0.00019,0.03911,0.40745,0.55344)		$\rho_1 + \rho_2 + \rho_3 + \rho_4 = 1.0 > 0.5$, $\rho_4 = 0.55344 > 0.5$	A_4
UMT-AHP-EDC	(0.00019,0.03911,0.40745,0.55344)	1.2139,1.1814, 0.8118,0.6058		A_4
UMT-EWM-AHP-CDRT	(0.00000,0.03335,0.35032,0.61633)		$\rho_1 + \rho_2 + \rho_3 + \rho_4 = 1.0 > 0.5$, $\rho_4 = 0.61633 > 0.5$	A_4
UMT-EWM-AHP-EDC	(0.00000,0.03335,0.35032,0.61633)	1.2263,1.1988,0.8961,0.5206		A_4

As shown in Table 9, the weights of the evaluating indicators can be divided into 3 groups with the EWM method. The weights of the first group (a total of 9 indicators) are 0.02937, and the weights of the second group (a total of 7 indicators) are 0.05874.

In practice, it is almost impossible that so many indicators have the same weights. Therefore, it is doubtful to use the EWM method to determine the indicator weights. After careful observation, the weights of X_{23} , X_{13} , and X_{12} are 0.02937, which is the minimum weight. It is obviously unreasonable, because X_{23} , X_{13} , and X_{12} are very important indicators for the evaluation of GM. The EWM is a pure objective method, which disregards the subjective opinions in the evaluation process. It is unreasonable to use only the EWM to determinate the evaluating indicator weight.

Similarly, the weights of each evaluating indicator for flue gas, which contain X_{19} , X_{20} , X_{21} , is 0.03722 with the EWM method. X_{19} and X_{20} are mainly derived from blasting exhaust gas and mining machinery exhaust gas, and X_{21} is mainly derived from the crushing process of the crushing sta-

tion and transportation dust. The emissions of X_{21} are substantially larger than the emissions of X_{19} or X_{20} for BM. The AHP is much closer to the actual situation than the EWM. The AHP adopts experts' subjective opinions, which is better than the EWM in determining the weights of the evaluating indicator for GM in BM.

According to the AHP and EWM coupling, the EWM-AHP is obtained. The EWM-AHP avoids the mistakes in the EWM and AHP. The weights of evaluating indicators are consistent with the actual situation with the EWM-AHP. The GM grades for the Yirui limestone mine and Mingguang limestone mine are shown in Table 13 for comparison. The GM grades for the Mingguang limestone mine are rated as A_1 with CDRT. However, the GM grades are rated as A_2 with EDC. Table 8 shows single indicator measure values that are concentrically distributed at A_1 and A_2 for the Mingguang limestone mine, which echoes GM grades. CDRT is stricter than EDC.

According to the actual situations of GM in the two mines, it can be speculated that UMT-EWM-AHP-CDRT is

TABLE 11: Weights of the evaluating indicator for Mingguang limestone mine. The underlined indicates the smallest five evaluating indicator weights for the EWM-AHP method. The bold values indicate the largest five evaluating indicator weights in the EWM-AHP method.

Evaluating indicator	EWM	Weight AHP	EWM-AHP	Evaluating indicator	EWM	Weight AHP	EWM-AHP
X_1	0.02421	0.01914	<u>0.01151</u>	X_{14}	0.04842	0.04261	0.05124
X_2	0.04842	0.01914	0.02302	X_{15}	0.04842	0.03023	0.03635
X_3	0.02421	0.03238	0.01947	X_{16}	0.04842	0.03722	0.04476
X_4	0.02421	0.03238	0.01947	X_{17}	0.03169	0.03722	0.02930
X_5	0.04842	0.01437	0.01728	X_{18}	0.02944	0.03722	0.02722
X_6	0.02752	0.01316	<u>0.00900</u>	X_{19}	0.02491	0.03722	0.02303
X_7	0.04842	0.00767	<u>0.00922</u>	X_{20}	0.03094	0.03722	0.02860
X_8	0.04842	0.03635	0.04371	X_{21}	0.02566	0.03722	0.02372
X_9	0.04842	0.02229	0.02681	X_{22}	0.02421	0.01241	<u>0.00746</u>
X_{10}	0.04842	0.01331	<u>0.01600</u>	X_{23}	0.04842	0.15961	0.19194
X_{11}	0.04842	0.01514	0.01821	X_{24}	0.02421	0.04289	0.02579
X_{12}	0.04842	0.06134	0.07376	X_{25}	0.03094	0.04623	0.03553
X_{13}	0.04842	0.07023	0.08445	X_{26}	0.04842	0.08578	0.10315

TABLE 12: Evaluating indicators, Euclidean distances, credible degree recognitions, and GM grades for Mingguang limestone mine.

Method	Comprehensive evaluation vector	Euclidean distance (d_i)	Credible degree recognition	GM grade
UMT-EWM-CDRT	(0.21444,0.41571,0.15789,0.21196)		$\rho_3 + \rho_4 + \rho_1 = 0.58429 > 0.5,$ $\rho_2 + \rho_1 = 0.63015 > 0.5$	A_1
UMT-EWM-EDC	(0.21444,0.41571,0.15789,0.21196)	0.9272,0.6762,0.9863,0.9299		A_2
UMT-AHP-CDRT	(0.34136,0.41217,0.15012,0.09634)		$\rho_4 + \rho_3 + \rho_1 = 0.58783 > 0.5,$ $\rho_2 + \rho_1 = 0.75354 > 0.5$	A_1
UMT-AHP-EDC	(0.34136,0.41217,0.15012,0.09634)	0.7972,0.7028,1.0090,1.0609		A_2
UMT-EWM-AHP-CDRT	(0.36355,0.41116,0.11920,0.10608)		$\rho_4 + \rho_3 + \rho_1 = 0.58884 > 0.5,$ $\rho_2 + \rho_1 = 0.77472 > 0.5$	A_1
UMT-EWM-AHP-EDC	(0.36355,0.41116,0.11920,0.10608)	0.7743,0.7102,1.0432,1.0557		A_2

TABLE 13: GM grades for Yirui limestone mine and Mingguang limestone mine.

Mine	EWM		UMT AHP		EWM-AHP	
	CDRT	EDC	CDRT	EDC	CDRT	EDC
Yirui limestone mine	A4	A4	A4	A4	A4	A4
Mingguang limestone mine	A1	A2	A1	A2	A1	A2

the most reasonable method among the 6 methods for the evaluation of GM grades in BM. The second one is UMT-EWM-AHP-EDC. The remaining four methods do not make sense. In addition, safety should be the basic condition for evaluating the GM grade; therefore, if X_8 (casualties per million man hours) is evaluated as A_1 , the GM grade is A_1 .

4. Discussion and Conclusions

The implementation of GM can improve the quality of economic growth for BM. However, the traditional evaluation

of GM is rarely targeted at BM and a focus on multiple uncertainty factors is rare too. The traditional evaluation of GM has defects in the selection of hierarchies, indicators, and indicator weights.

In this paper, UMT was employed to establish the evaluation models for BM. By investigating the pollutants and green ways and the engineering status of BM, we determine evaluating indicators and evaluating hierarchies to reduce the effects of unreasonable hierarchies and indicators in the conventional methods. Moreover, three methods were adopted to determinate indicator weights for comparison,

including AHP that considers expert experience, EWM that considers the objective data, and a combination of EWM-AHP. CDRT and EDC were employed to determine the grades of GM. A total of six evaluation methods were applied to two limestone mines in China. Finally, according to comparative analysis, UMT-EWM-AHP-CDRT was considered the most reasonable method of GM evaluation for BM that considers uncertainty factors and multiple indicator weights.

UMT-EWM-AHP-CDRT is very applicable, not only can determine the green mining grades, but also can provide guidance for improving the current situation of green mining. Finally, based on UMT, we developed a reasonable method of GM evaluation for BM. At present, there is no unified standard for green mining classification, which still needs to be further studied. Besides, LU has a wide application prospect, and its application in other fields in the future also needs further study.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

This study was partially funded by the National Natural Science Foundation of China (No. U1802243, No. 41672317), Hubei Province Technical Innovation Special (major projects) (No. 2017ACA184), and Major Science and Technology Projects of WUST Cultivate Innovation Teams (No. 2018TDX01).

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