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An Integrated Gray DEMATEL and ANP Method for Evaluating the Green Mining Performance of Underground Gold Mines

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Abstract: Green mining (GM) can achieve the harmonious development of mineral resource exploitation and environmental protection. Performance evaluation is the key to promoting GM. This research explores favorable methods to evaluate the green mining performance (GMP) of underground gold mines. First, according to the specific characteristics of underground gold mines, an evaluation criteria system for GM is formulated. Meanwhile, the weights are calculated using an integrated gray DEMATEL and ANP technique, which considers the correlation between indicators. Subsequently, the solution methodology for performance evaluation is proposed based on normalization of indicators. Finally, six underground gold mines are utilized as case studies to verify the methodological feasibility. The results of the empirical study show that there is a significant gap between ordinary mines and pilot green mines, and this study, via comparison analysis and cause–effect analysis, gives direction for mines improvement. Not only will the work provide technical and theoretical support for the evaluation and construction of similar green mines, it will also serve as a reference for government policy implementation.

Keywords: green mining; green mining performance; integrated Gray DEMATEL and ANP; evaluation system; sustainable development; underground gold mines

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1. Introduction

The mining industry provides raw materials for socio-economic development, while unregulated mining operations may also cause serious ecological problems [1]. China, as a major mining country, faces an even tougher situation [2]. To solve the environmental problems and achieve sustainable development, China has proposed a green mining (GM) policy [2–4], with financial and tax incentives. Furthermore, many mines have joined the ranks of GM construction. Now comes the question of which mine is performing better. The government has to implement policy according to green mining performance (GMP), and mine enterprises have to improve by comparison. GMP evaluation of mines using appropriate and scientific approaches becomes particularly important [5,6], playing a critical role in promoting GM [6,7].

Considering the diversity of GM evaluation criteria, this would be a complicated matter of multicriteria decision-making (MCDM). Scholars have conducted studies on specific mines using different methods. Zhou et al. [1] adopted a fuzzy comprehensive evaluation method to assess the green surface mine in China. Chen et al. [5] put forward a Driver–Pressure–State–Impact–Response framework to formulate the GM evaluation indicator, and the PCA method was used to evaluate the interactions between human and environmental systems. Jiskani et al. [8] analyzed the Green and climate-smart mining of open-pit mines, fuzzy AHP was applied to determine weights, and the Grey clustering method was used to classify the result into concrete levels. Liang et al. respectively assessed the GMP through the Hesitant Fuzzy ORESTE–QUALIFLEX method [6] and MCDM combined with a picture fuzzy information approach [9]. Qi et al. [10] proposed an evaluation system of GM construction, and determined the critical factor of GM by the two-step fuzzy DEMATEL model. Based on uncertainty measurement theory, Wang et al. [11] evaluated GM grades with six coupled methods, and finally selected the optimal method by credible degree recognition.

Although the above research addressed similar GMP evaluation tasks, the criteria system and MCDM methods are quite different. This is because the mineral species and mining method have to be considered while developing the evaluation criteria, and MCDM methods are selected based on the collected indicator data. Thus, it would be significant to develop specific appropriate and efficient evaluation methods [9,12]. For this purpose, in order to formulate an applicable GMP evaluation system to underground gold mines, the characteristics of mines have to be fully considered [13], and the principles of GM [14–17] are required for referencing.

The study area is located in Jiaodong Peninsula, one of the most important gold origins for China [18]. Firstly, the geological conditions in the region are exceedingly complicated, with fault structures and fractured zones [19] dispersed across the mining sites, posing safety risks, and the risk for accidents to occur is greater due to underground space limitations. Accordingly, safety production (SP) holds great meaning for GM, with this criterion being the basic condition for evaluating GMP [1,11]. Secondly, waste rock stockpiles and unregulated discharge of tailings [20] can cause environmental damage. However, the utilization rates of solid waste are quite low in local underground gold mines. To some extent, these solid wastes can be used in alternative ways. For example, tailings can be used for underground filling, and the waste rock crushed into stone as building materials. Thus, the comprehensive utilization (CU) of mining solid wastes should be considered as the evaluation criterion for GMP [7,21]. Thirdly, gold ore mined by drilling and blasting, emits dust and blasting fumes [22]. In addition, hydrogenated tailings can contaminate water bodies and soil without proper disposal [23–25]. Green emphasizes environmental protection (EP), which is also an essential criterion for GMP. Finally, the original intention of GM is to obtainn resources in an eco-friendly and efficient manner, with mining efficiency (ME) [26] representing the key component. In summary, SF-CU-EP-ME should be considered comprehensively to formulate a GMP evaluation criteria system for underground gold mines.

For the sake of relative fairness, indicators should be accurately calculable to eliminate subjective judgments. In terms of weight, the determination is a multilevel, complex, and comprehensive procedure, thus correlation and constraints between the indicators [1] should be considered. However, previous GMP evaluation research works have not employed indicator correlations to calculate weights. Therefore, it is necessary to devise a method for determining weights based on the relationship between indicators. For this goal, integrated DEMATEL-ANP [27,28] is extremely capable of solving this issue; DEMATEL is used to determine the factors influencing interaction, with ANP used to obtain the relative weight. However, crisp values occur in this method, which is inappropriate and imprecise for describing the information [9,29,30]. To conquer this limitation, the gray theory was exploited to transform crisp values into interval gray numbers, which improves the reality of decision-making data. Consequently, gray DEMATEL is adopted to examine the causal relationship in an uncertain environment, and then the ANP method to calculate the relative weight based on the influential relationship acquired from gray DEMATEL [31,32]. Finally, metrics need to be converted into scores. However, traditional grading methods, will yield no distinction between the same levels. A linear transformation approach would be a reasonable option.

In summary, an evaluation system is established to evaluate GMP for underground gold mines. In this respect, an evaluation criteria system is formulated in consideration of the characteristics and principles of GM, while an integrated gray DEMATEL and ANP method are devised to determine the relative weights, and a linear transformation strategy is used to convert index values to corresponding scores. Compared to other methods, the criteria system constructed in this work is more target-oriented. In addition, the indicators can be calculated accurately to avoid human error, and the weighting and converting procedures of indicators are relatively fair. With regard to the above advantages, this study is rendered both feasible and reasonable.

The structure of this paper is designed as follows. Section 2 introduces the methodology in detail, including the technical route, indicators, and method. Section 3 provides a case study using the collected decision-making data from experts and indicator values from underground gold mines, with the results computed. Section 4 makes cause–effect and comparative analysis based on the results, and some managerial implications are also involved. Section 5 summarizes the paper and presents suggestions.

2. Methodology

In this section, the clear GMP evaluation system for underground gold mines is established, as well as the calculation method of each indicator. Procedures of the adopted integrated methods are described in detail. The entire flowchart is indicated in Figure 1.

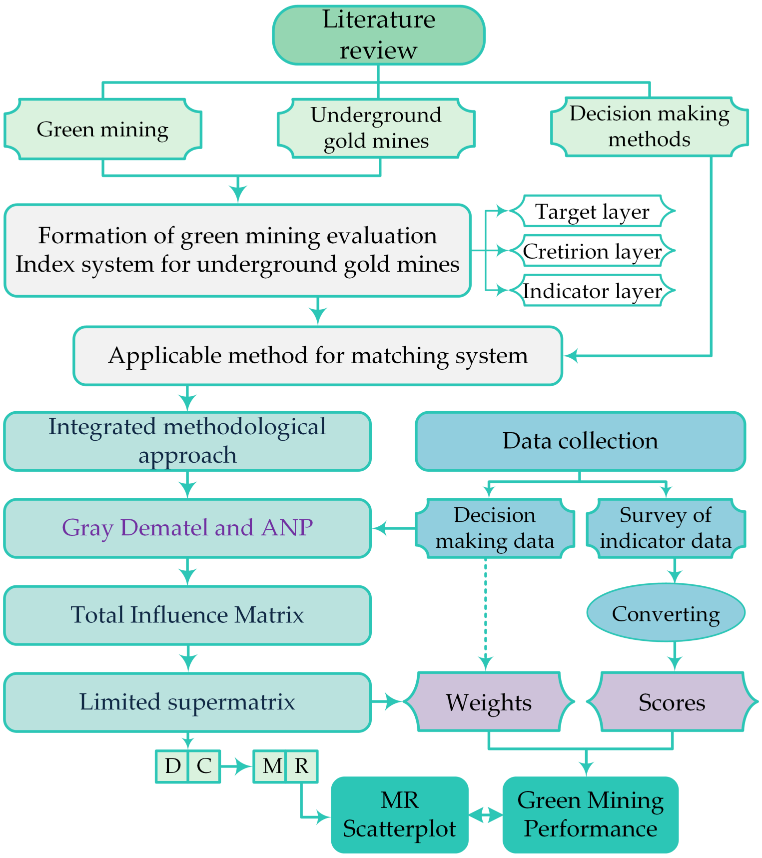

Figure 1. Flowchart for evaluating GMP of underground gold mines.

2.1. Evaluation Criteria

The GMP evaluation criteria for underground gold mines are first identified. Selecting suitable indicators is essential for the performance evaluation of green mines [6]. To find suitable indicators for the criteria layer, some principles must be followed. Data with easy accessibility principle is a prerequisite. The calculable principle ensures data accuracy and relative fairness, and the independence principle guarantees sensible structure. Within the SF-CU-EP-ME framework defined earlier, indicator layers also need to be determined, considering the specific characteristics of underground gold mines and referencing literature [1,5,6,9,11] related to GMP, the indicators under each criterion level were determined gradually. The evaluation system includes four criteria and twenty indicators. For clarity, the framework is shown in Figure 2. The calculation method of each indicator is shown in Table A1, and the following are thorough explanations of these criteria.

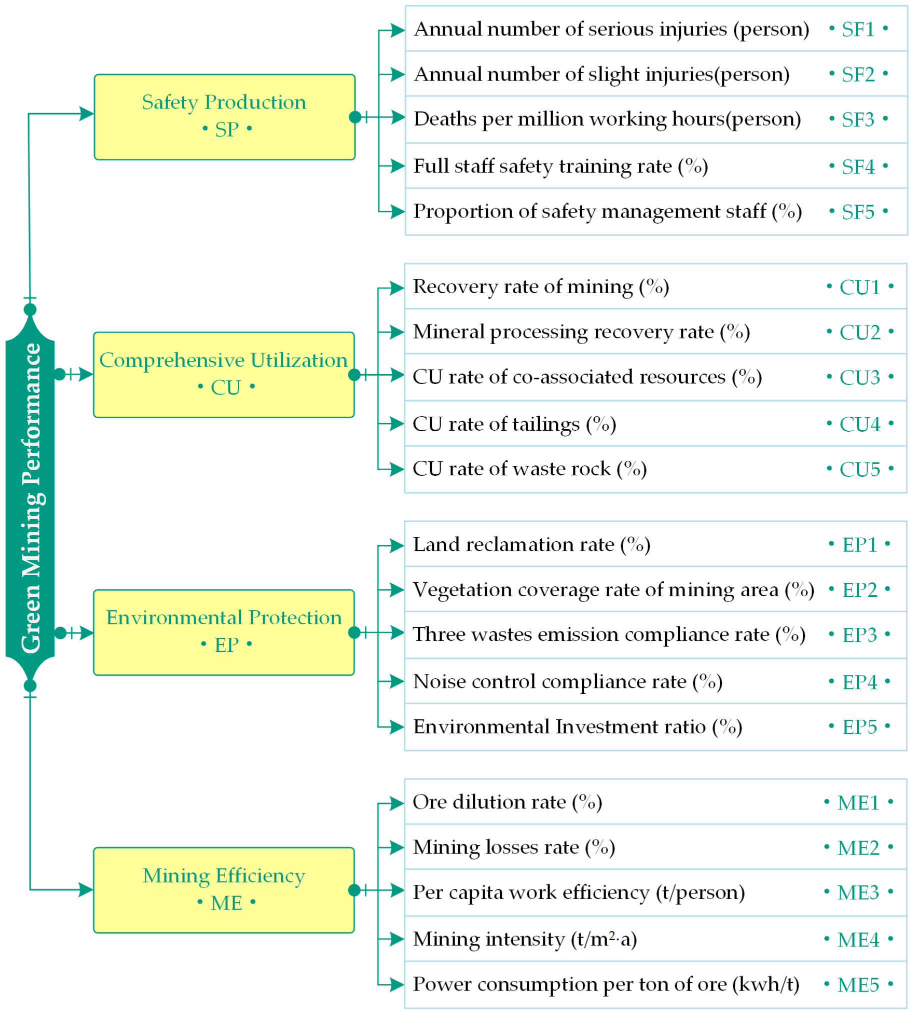

Figure 2. GMP evaluation criteria system for underground gold mines.

2.1.1. Safety Production

Safety production is a policy that must be followed by mining enterprises, requiring the minimization of work-related injuries among workers. Consequently, three indications of work-related injuries [1,11] are identified, containing the annual number of serious injuries SF1, annual number of slight injuries SF2 and deaths per million working hours SF3, these indicators meet smaller-is-better. Safety training [33,34] and management are critical for improving the safety situation in underground mining. Workers' emergency reaction capabilities may be improved by safety training, which can successfully prevent and reduce the occurrence of safety accidents. Safety management [1,34] is primarily concerned with the organization and implementation of enterprise safety management planning, guidance, inspection, and decision making. It is also the critical link in ensuring that production is conducted in the best possible safety conditions. As a result, the full staff safety training rate SF4 and the proportion of safety management staff SF5 were determined, with higher is better.

2.1.2. Comprehensive Utilization

Comprehensive utilization of resources includes two aspects. One is to improve the utilization rate of the resources themselves, and the other is to realize the comprehensive utilization of solid waste. In the case of underground gold mines, the resources are mainly gold metal or other associated resources. From this aspect, improving the mining recovery rate (CU1) [7], mineral processing recovery rate (CU2) [5] and the utilization rate of associated resources (CU3) [6,14] are conducive to the CU of resources. The solid waste includes waste rock from mining and tailings from processing, which will occupy industrial land and pollute the environment without depositing. Actually, the waste produced in gold mines is also a valuable resource, which is worth developing and utilizing [13,14]. Through comprehensive utilization, the waste can be turned into treasure, which not only can solve the problem of solid waste pollution, but can also create economic benefits. Therefore, comprehensive utilization rate of tailings (CU4) [7,8] and waste rock (CU5) [8] are determined.

2.1.3. Environmental Protection

On the one hand, the mining landscape is very important. However, waste rock piles and tailing ponds occupy land, which destroys the natural landscape, and causes environmental pollution. Land reclamation is the activity of restoring damaged land to a usable state, the strength can be demonstrated by land reclamation rate EP1 [1,5,11,14]. The main focus of mine greening is to restore vegetation by greening and planting barren areas to increase the vegetation coverage rate of mining area (EP2) [5,6,11,14] and fulfill the goal of optimizing the landscape. On the other hand, pollution emission [3,7] control is extremely important for environmental protection, including three wastes [6] and noise [8]. Pollution emissions need to meet national standards, thus two indicators (EP3, EP4) related to compliance rate are used to describe the process. Finally, the environmental investment ratio (EP5) [5,26], is one of the main indicators to measure the harmonious relationship between environmental protection and economic development, which can improve the quality of the environment and prevent ecological degradation. All these indicators present with higher being better.

2.1.4. Mining Efficiency

Ore dilution refers to the reduction of ore grade due to the mixing of waste rock during the mining process. Ore losses describe the phenomenon of ore being discarded or not fully extracted during mine production due to various reasons (such as complex geological conditions, improper mining methods and transportation problems, etc.). Ore dilution and losses severely affect mining efficiency [26], with the ore dilution rate (ME1) [14] and mining losses rate (ME2) [14] being used to quantify this process. Per capita work efficiency (ME3) [11] is used for measuring the labor efficiency of mining enterprises, with higher values for the mechanization degree and mining efficiency being better. Mining intensity in underground mines refers to the annual amount of ore produced per square meter of mining area. Mining intensity [35] is high if there is good continuity and a high rate of progress of mining preparation, and more blocks are being retrieved at the same time; conversely, mining intensity is poor when continuity, mining area, and rate of block retrieval are low. Mining intensity is a comprehensive indicator reflecting the mining efficiency, denoted by ME4. During the mining process, it is highly efficient to achieve the same production goal with less energy. Hence, ME5 is exploited to reflect the energy consumption [5,7,14] level of mining.

2.2. Integrated Gray DEMATEL and ANP

DEMATEL is a system science technique proposed by American scholars A.Gabus and E.Fontela [36] in 1972. It is applicable for analyzing the interdependent relationships among factors in a complex system and ranking them for long-term strategic decision making [37]. The Gray DEMATEL technique is upgraded from the typical DEMATEL approach, the general steps are gray number normalization and clarification, and the remaining steps are consistent with the typical DEMATEL technique.

To obtain the initial decision data, decision-makers are asked to specify the influence degree of one indicator on another indicator, utilizing five different integer scales [36], as shown in Table 1. Next, according to Table 1, crisp values are converted into interval gray numbers, which contain the upper and lower bounds. The Gray DEMATEL method consists of the following steps.

Table 1. Relative influence index.

Crisp Values	Linguistic Variables	Interval Gray Number
0	No influence	[0, 0]
1	Low influence	[0, 0.25]
2	Medium influence	[0.25, 0.5]
3	High influence	[0.5, 0.75]
4	Very high influence	[0.75, 1]

Step 1: Normalization of the upper and lower bounds.

$$\begin{cases} \underline{\otimes}\tilde{x}_{ij}^{k} = \left(\underline{\otimes}x_{ij}^{k} - \min \underline{\otimes}x_{ij}^{k}\right) / \triangle_{\min}^{\max} \\ \overline{\otimes}\tilde{x}_{ij}^{k} = \left(\overline{\otimes}x_{ij}^{k} - \min \overline{\otimes}x_{ij}^{k}\right) / \triangle_{\min}^{\max} \\ \triangle_{\min}^{\max} = \max \overline{\otimes}x_{ij}^{k} - \min \underline{\otimes}x_{ij}^{k} \end{cases} \tag{1}$$

where $\underline{\otimes}\tilde{x}_{ij}^{k}$ is the lower bound of the expert's raw score after transforming it into the interval gray number. Correspondingly, $\overline{\otimes}\tilde{x}_{ij}^{k}$ is the normalized upper bound.

Step 2: Converting fuzzy data into crisp Scores.

$$\begin{cases} Y_{ij}^{k} = \frac{\left(\underline{\otimes}\tilde{x}_{ij}^{k}\left(1-\underline{\otimes}\tilde{x}_{ij}^{k}\right)+\left(\underline{\otimes}\tilde{x}_{ij}^{k}\times\underline{\otimes}\tilde{x}_{ij}^{k}\right)\right)}{\left(1-\underline{\otimes}\tilde{x}_{ij}^{k}+\overline{\otimes}\tilde{x}_{ij}^{k}\right)} \\ Z_{ij}^{k} = \underline{\otimes}\tilde{x}_{ij}^{k} + Y_{ij}^{k}\triangle_{\min}^{\max} \end{cases} \tag{2}$$

Y_{ij}^{k} is the calculated preliminary crisp value, and Z_{ij}^{k} is ultimate crisp value.

Step 3: Generating the direct influence matrix combining experts' weights.

$$Z_{ij} = w_1 Z_{ij}^{1} + w_2 Z_{ij}^{2} + \cdots + w_k Z_{ij}^{k} \tag{3}$$

where w_i is the attribute weight of expert i, and the sum of $w_1, w_2, \cdots, w_k$ is one.

As a result, make the diagonal elements as zero, the group direct influence matrix is Z.

$$Z = \begin{bmatrix} 0 & z_{12} & \cdots & z_{1n} \\ z_{21} & 0 & \cdots & z_{2n} \\ \vdots & \vdots & 0 & \vdots \\ z_{n1} & z_{n2} & \cdots & z_{nn} \end{bmatrix} = \left(z_{ij}\right)_{n\times n} \tag{4}$$

Step 4: Normalizing the initial influence matrix.

$$X = \frac{Z}{\max\left(\sum_{j=1}^{n} x_{ij}\right)}, 1 \le i \le n \tag{5}$$

Step 5: Constructing the total influence matrix T.

$$T = \left(X + X^2 + X^3 + \cdots + X^{h\to\infty}\right) = X(1-X)^{-1} \tag{6}$$

Step 6: Producing the influential relation map.

$$M_i = D_i + C_i = \sum_{j=1}^{n} t_{ij} + \sum_{i=1}^{n} t_{ij}$$
$$R_i = D_i - C_i = \sum_{j=1}^{n} t_{ij} - \sum_{i=1}^{n} t_{ij} \quad (7)$$

Let D_i denote the sum of rows, which indicates the degree of influence, while C_i represents the sum of columns, which shows the degree of being influenced. M_i denotes centrality and prominence in the system, whereas R_i denotes the causality of indicators, and reflects the relationship in the system.

At last, the total influence matrix is regarded as the unweighted supermatrix of ANP [38]. After normalization, we can obtain the weighted supermatrix, while it self-multiplies, has converged and become a stable supermatrix [39]. This new matrix is called a limited supermatrix, and the relative weights of each criterion can be obtained from this matrix.

2.3. Performance Evaluation

There are large gaps in the collected evaluation data, and normalization of the data is necessary, which facilitates scientific calculations and accuracy.

For "smaller-is-better" indicators, the normalized value $x_i(k)$ can be calculated as:

$$x_i(k) = \frac{\min(x_i)}{x_i(k)}, \; for \; 1 \le i \le n, \; 1 \le k \le m. \quad (8)$$

For "larger-is-better" indicators, the normalized value $x_i(k)$ can be calculated as:

$$x_i(k) = \frac{x_i(k)}{\max(x_i)}, \; for \; 1 \le i \le n, \; 1 \le k \le m. \quad (9)$$

where $\max(x_i)$ and $\min(x_i)$ represent the maximum and minimum values.

$$Scores = \sum_{i=1}^{n} w_i x_i(k), \; i = 1, \cdots, n; \; k = 1, \cdots, m. \quad (10)$$

Finally, a simple additive weighting method [40] is used to rank the performance, which reflects the advantages of indicators while maintaining simplicity of calculation [41]. The weight of each indicator can be calculated by the GDANP method, the normalized evaluation data multiplied by weights obtain the score of each indicator, and summing up the scores gives the evaluation results, as shown in Equation (10).

3. Case Study

3.1. Case Description

Shandong Gold Mining Co., Ltd is the largest gold producer in China, and it is devoted to GM for environmental protection and sustainable development. This corporation has so far established a series of national pilot green mines, with the remainder of the numerous mines still under construction. Discovering the gaps between the pilot sites and the rest of the mines becomes crucial, facilitating reference and experience learning. For this purpose, six underground gold mines were selected. Three of them are pilot green mines (denoted as M1, M2, M3), the rest are under construction (denoted as M4, M5, M6).

M1 has taken the initiative to collaborate with nationally renowned scientific research institutes, picking appropriate mining methods based on rock classification, and optimizing mining parameters. To accomplish safe and effective mining, the upward approach filling mining technique, wide approach filling mining method, and automated pan area mining method are employed thoroughly. Mining loss and depletion rates have been significantly lowered. M2 focuses on the comprehensive utilization of resources, which applies the medium-deep hole pre-controlled top section filling mining method to improve the ore recovery rate. At the same time, the beneficiation process has been modified to improve the recovery rate of gold. M3 is dedicated to the reuse of solid waste. Parts of the tailings and waste rocks are used to solidify and fill the quarry area, while the remainder is utilized to manufacture concrete bricks, resulting in greater economic advantages and the transformation of trash into treasure. Each mine bears its own unique characteristics, and by adjusting to local conditions, each mine has achieved significant achievements in the GM process. Therefore, it is essential to pick these three pilot mines as a study reference.

3.2. Data Collection

Data collection is divided into two parts: expert decision data and evaluation data of underground mines. Expert decision data were acquired from the questionnaires. Three conditions must be met for the selection of experts: first, the experts must be independent of the mines involved in the evaluation; second, they must have extensive work experience in underground gold mining; and third, they must be familiar with or have participated in the evaluation of green mining. After screening, six experts were confirmed, and the statistic information and gray weights of the selected experts are illustrated in Table 2.

Table 2. Statistics of experts in GM.

Experts	Education	Working Years	Position	Gray Weights
E1	Bachelor	17	Engineer	[0.3, 0.4]
E2	Doctor	28	Professor	[0.7, 1.0]
E3	Master	23	Deputy mine manager	[0.5, 0.6]
E4	Bachelor	19	Senior Engineer	[0.3, 0.5]
E5	Master	30	Mine manager	[0.6, 0.8]
E6	Doctor	25	Supervisors	[0.7, 0.9]

The questionnaire was completed by all six of the selected experts, who carefully answered pertinent topics. The initial decision matrix can be derived from the surveys, and all of the data are valid. The expert decision matrix was calculated by using the GDANP method, the total influence matrix Table A2, the weighted supermatrix in Table A3 and the limited supermatrix Table A4 can be obtained, respectively.

The evaluation data of underground gold mines are obtained through onsite investigation, assisted by the relevant mine production manager. The collected original evaluation data are shown in Table A5. For these "smaller-is-better" indicators (SP1, SP2, SP3, ME1, ME2, ME5), which can be normalized through Equation (8), indicators with a minimum value of zero need to be handled by the overall moving method, and the rest are "larger-is-better" indicators, which can be normalized by Equation (9). The normalized evaluation data are shown in Table A6.

3.3. Results

In this study, the formulated evaluation index comprises three hierarchical layers: the target layer, the criterion layer, and the indicator layer. Based on corresponding principles, the evaluation system for underground mines including four criteria and twenty indicators are determined.

Considering the correlation of indicators, an integrated evaluation method based on GDANP is used to calculate the weight of indicators, from the limited supermatrix, the weight of each indicator can be calculated, as shown in Table 3. Finally, the ranking order of the criteria is CU$\succ$ME$\succ$EP$\succ$SP, CU becomes the most important criterion for GM.

The score of each underground gold mine can be calculated according to Equation (10), and the results are shown in Table A7. For clarity, Figure 3 depicts the results. There is a clear gap between the mines under construction and the pilot green mines, and this also demonstrates the validity of the method proposed in this study, which can efficiently discriminate between two types of mines. Finally, the rankings for these mines are as follows: M3≻M1≻M2≻M5≻M4≻M6.

Table 3. Weights of indicators computed by using GDANP.

Criteria	Weight	Rank	Indicator	Local Weight	Global Weight	Rank
SP	0.1881	4	SP1	0.2103	0.0396	14
			SP2	0.1480	0.0278	16
			SP3	0.2335	0.0439	11
			SP4	0.1816	0.0342	15
			SP5	0.2263	0.0426	12
CU	0.3130	1	CU1	0.3035	0.0950	2
			CU2	0.0443	0.0139	17
			CU3	0.0321	0.0101	20
			CU4	0.3402	0.1065	1
			CU5	0.2799	0.0876	3
EP	0.2384	3	EP1	0.2370	0.0565	7
			EP2	0.1676	0.0399	13
			EP3	0.2085	0.0497	9
			EP4	0.0577	0.0138	18
			EP5	0.3291	0.0785	5
ME	0.2606	2	ME1	0.1736	0.0452	10
			ME2	0.2139	0.0558	8
			ME3	0.2563	0.0668	6
			ME4	0.3070	0.0800	4
			ME5	0.0489	0.0127	19

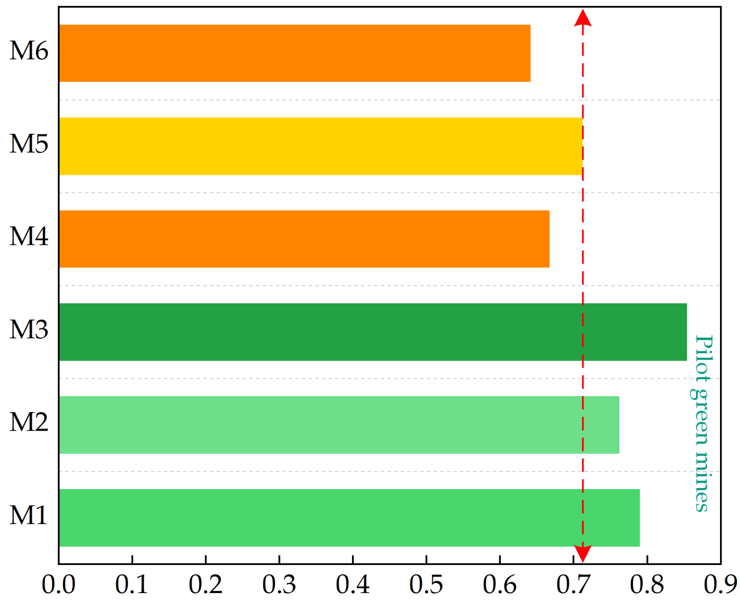

Figure 3. The GMP evaluation results for underground gold mines.

4. Discussions

4.1. Cause–Effect Analysis

The influence index and relationship index are the core factors of DEMATEL analysis [10]. The former indicates the factor's ability to influence the system. The larger the value, the higher the degree of influence. The latter has positive and negative values, belonging to the cause group and effect group, respectively. This is because the relationship index is calculated by $(D_i - C_i)$, positive values indicate the influence degree exceeds the influenced degree, and negative values are dominated by the influenced degree. Theoretically, the cause group affects the factors in the effect group, thus they are the system-identified issues that demand priority improvement. The results are shown in Table 4.

Table 4. Prominence and relation of each indicator.

	Row Sum (D_i)	Column Sum (C_i)	Influence Index	Relationship Index
SP1	0.8226	1.0446	1.8672	−0.2220
SP2	0.5563	0.9534	1.5098	−0.3971
SP3	0.9574	0.8633	1.8207	0.0941
SP4	0.8058	1.1066	1.9123	−0.3008
SP5	1.0360	0.5023	1.5383	0.5337
CU1	1.0911	0.4550	1.5461	0.6362
CU2	0.2505	0.2636	0.5142	−0.0131
CU3	0.1804	0.1330	0.3135	0.0474
CU4	1.5329	1.2658	2.7986	0.2671
CU5	1.3308	0.8463	2.1770	0.4845
EP1	1.0006	1.6760	2.6766	−0.6754
EP2	0.6908	1.3902	2.0810	−0.6993
EP3	0.9933	1.0061	1.9993	−0.0128
EP4	0.2978	0.4253	0.7231	−0.1274
EP5	1.5072	1.8853	3.3925	−0.3781
ME1	0.6488	0.1690	0.8178	0.4799
ME2	0.7502	0.4161	1.1663	0.3341
ME3	0.6951	0.7732	1.4683	−0.0780
ME4	0.9986	0.5897	1.5883	0.4089
ME5	0.1326	0.5142	0.6468	−0.3817

A cause–effect diagram is a tool to logically organize and graphically display the causes associated with specific effects [29]. The influence and relationship values were used to plot the cause–effect diagram, as shown in Figure 4. Typically, this diagram is divided into four categories, core causal, inferior causal, core effect and inferior effect.

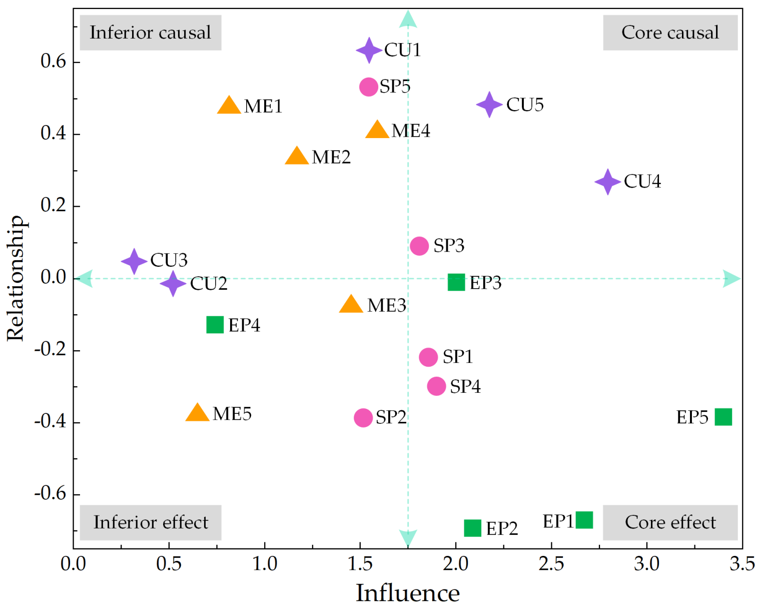

Figure 4. Casual–effect diagram of indicators.

The core causal group with large prominence and positive relation, CU5, CU4, and SP3 are concluded in this cluster, elements in this group have the topmost priority for improvement. The inferior causal group with small prominence and positive relation, SP5, CU1, CU3, ME1, ME2, ME4 are classified in this region, they require immediate improvement but with high priority. SP2, CU2, EP4, ME3, ME5 with small prominence and negative relation, affiliated to the inferior effect group, are improved indirectly with medium priority. The rest with large prominence and negative relation belong to the core effect group, which are affected by elements in other groups. In this way, the elements in the causal groups are improved, and the corresponding effect groups will be upgraded as well. Therefore, the order of improvements can be determined based on the priority of indicators, as shown in Table A8, red for topmost priority, purple for high priority, and cyan for medium priority.

4.2. Comparative Analysis

A comparative analysis is required to understand the strengths and weaknesses of specific mines. Figure 5 indicates the performance of the underground gold mine in different fields. From each dimension, M1 and M2 underperform in terms of SP, M4, M5, and M6 has a poor degree of CU, M6 has the lowest EP score, and M4 and M6 have significant weaknesses in terms of ME. Each mine includes aspects that need to be improved when broken down into distinct indicators. Table A8 demonstrates the prospective improvement elements for each mine.

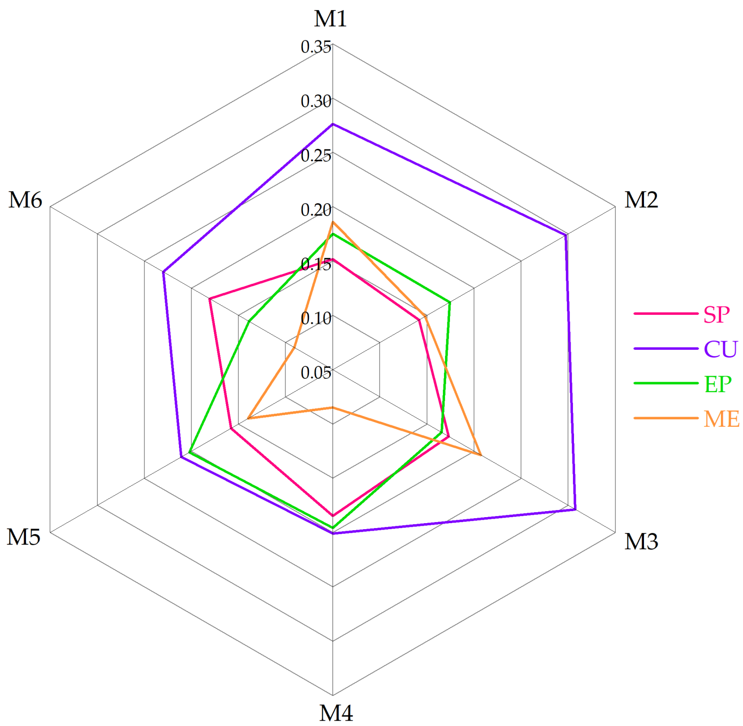

Figure 5. The GMP distributions of underground gold mines.

From a holistic view, the pilot green mines are developed in a more balanced way, and they have great advantages in terms of CU. This is because CU has a high degree of association with other indicators, especially CU4 and CU5 which are used for underground filling. These not only control ground pressure and prevent surface collapse (benefits for SP), but also solve the EP pressure, and the filling mining method improves ME. Correspondingly, these are the driving factors for green mines to enhance CU.

In terms of scores, M3 performs the best, M1 and M2 still show space for improvement, M4 and M6 perform poorly and have a large gap between the pilot green mine. M5 has the most potential to develop into a green mine.

More importantly, to validate the feasibility of this research, a comparative analysis with other related studies is crucial.

(1) Comparison of evaluation criteria

This paper proposed an evaluation criteria framework, applicable to underground metal mines. Compared with the most similar GMP evaluation study, the criteria system in the literature [9] is very abstract, which is not conducive to the accuracy of evaluation. Meanwhile, the selection of indicators was kept simple based on the essential requirements of green mining [7]. Thus, the easy accessibility of evaluation information is determined as a prerequisite to choosing indicators. The proposed evaluation system is flexible, and the criterion can be more specific in future studies.

(2) Comparison of weight determination methods

The analytic network process method is widely used for MCDM [42,43], but the calculation process is complicated. To compensate for the shortcomings of this single method, hybrid evaluation methods with ANP [44,45] were proposed. The weights in this research were determined using an integrated Gray DEMATEL and ANP approach, which was employed for the first time in the GMP evaluation sector. In comparison to other methods, this approach fully utilizes the correlation between indicators and simplifies the calculation process [39]. Therefore, the calculated weights are more reasonable.

(3) Comparison of the results

The GMP evaluation studies usually assess the same type of mines [6,9], and this paper selected three pilot green mines as control group. The proposed method is capable of distinguishing between two types of mines, which verifies the feasibility of this research. The results show that CU is the most important criterion in GM, and this can be corroborated by the related research [7]. Moreover, the cause–effect analysis provided a reasonable order for mine improvements, which has not been found in GMP evaluation studies. Thus, the proposed suggestions are more informative than similar studies.

To sum up, the advantages of proposed approaches summarized as follows:

- Evaluation indicators are specific and data easy to obtain, the calculability of evaluation information guarantees the relative fairness of evaluation.
- Weights are calculated by correlation between indicators, and with the cause–effect analysis guide for mine improvements, the suggestions are more informative.
- Data of six underground gold mines were collected, the proposed method can distinguish between two types of mines, which verify the feasibility of proposed method.

4.3. Managerial Implications

Management of mining processes and monitoring of their performance is a basic prerequisite for continual improvement [46], and the performance evaluation of mines is the key to promoting green mine construction [7]. Figure 6 reveals the role of evaluation in GM. The evaluation has profound implications and broad application value, pushing mines to practice green mining, and serving as a strong tool for the government to encourage policy implementation.

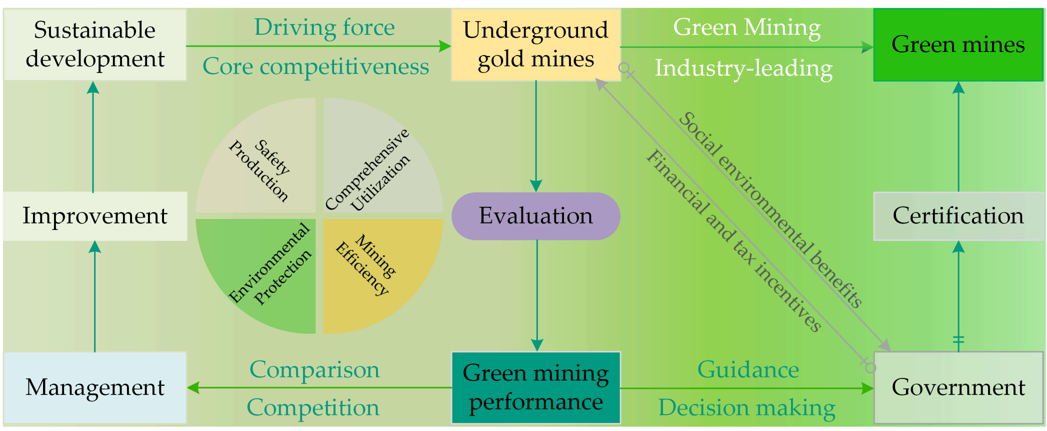

Figure 6. The role of evaluation in green mining.

Mines are compared in the evaluation process, and the results point out the advantages and weaknesses of mines, which indicate the way forward for improvement and upgrading. For sustainable development, mines have to identify and solve gaps; this purpose becomes the driving force for GM. When the mines have performed excellently in green mining and reached the industry-leading level, they will be recognized as green mines. The designation is certificated by the government, and evaluation plays an important role in this procedure, guiding the decision-making of the government. The mines create social environmental benefits, and the government supports financial and tax incentives to mines depending on the GMP, highlighting a mutually beneficial situation. Mines provide social and environmental benefits, while the government provides financial and tax incentives to mines based on GMP, creating a win–win scenario.

5. Conclusions

The integral elements of the GM for underground gold mines include safety production, comprehensive utilization of resources, environmental protection, and mining efficiency. In order to measure the GMP of different mines, an evaluation system is proposed in this study, which consists of four criteria and twenty indicators. Considering the correlation of indicators, an integrated GDANP method has been exploited to evaluate the GMP for six underground gold mines. The results demonstrate the rank order as well as the gap between the mines. Furthermore, the weaknesses of each mine are analyzed in a broad dimension, and the advantages of pilot green mines are explained in a reasonable manner. Subsequently, the cause–effect analysis categorizes indicators into four groups, with the priority defined by the prominence and relation of each indicator. To solve the gaps, mines have to implement improvements sensibly. Finally, this research explored the effect of evaluation on mining management and the government.

Indeed, there are some limitations to this study, e.g., the lack of evidence to prove which proposed method was the best. Perhaps the presented evaluation framework can be extended with other MCDM approaches. Indicators can be added to make the system more comprehensive, and the evaluation criteria can be improved in future studies.

In summary, this paper mainly evaluated the GMP for underground gold mines and provided ideas for improvements. The evaluation framework applies to underground metal mines, and some indicators in the formulated system are likely to work for similar environments. The proposed methodology can also be exploited in other evaluation studies where the indicators are correlated. The results of this research may be used as a reference for GM in other mines, as well as to assist government policy implementation.

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Abbreviations

The following abbreviations are used in this manuscript:

CU	Comprehensive utilization
EP	Environmental protection
GDANP	Gray DEMATEL and ANP
GM	Green mining
GMP	Green mining performance
MCDM	Multi-Criteria Decision-Making
ME	Mining efficiency
SP	Safety production

Appendix A

Table A1. Calculation method for indicators.

Indicator	Calculation Method	Unit
SP1	Number of serious injuries per year	person
SP2	Number of light injuries per year	person
SP3	Number of deaths/Million working hours × 10^6	person
SP4	Number of people receiving systematic security training/All staff × 100%	%
SP5	Number of people engaged in full-time safety production management/All staff × 100%	%
CU1	Mined ore/Reserves of ore owned by the mining area × 100%	%
CU2	Mass of useful fraction in concentrate/Mass of useful fraction in the ore inducted × 100%	%
CU3	Mass of co-associated minerals that have been utilized/Mass of contained co-associated minerals × 100%	%
CU4	Annual tailings utilization/Total annual tailings production × 100%	%
CU5	Annual amount of waste rocks utilized/Total amount of waste rocks produced annually × 100%	%
EP1	Reclaimed land area/Damaged land area × 100%	%
EP2	Greening area/Actual greenable area × 100%	%
EP3	Actual emission of three wastes/Permitted emission of three wastes × 100%	%
EP4	The area where the noise control meets the national standard/The noise area of the mine × 100%	%
EP5	Annual environmental protection investment/Annual revenue of the mine × 100%	%
ME1	(Geological grade of original ore - grade of extracted ore)/Geological grade of original ore × 100%	%
ME2	(Industrial reserves - actual ore mined)/Industrial reserves × 100%	%
ME3	Total monthly ore production/Number of all employees	t/person
ME4	The annual amount of ore mined from the mining face/Gross area of the back-mining area	$t/m^2 \cdot a$
ME5	Annual power consumption/Annual gold ore production	kWh/t

Table A2. The total influence matrix.

	SP1	SP2	SP3	SP4	SP5	CU1	CU2	CU3	CU4	CU5	EP1	EP2	EP3	EP4	EP5	ME1	ME2	ME3	ME4	ME5
SP1	0.0767	0.1590	0.1465	0.2019	0.1079	0.0014	0.0003	0.0001	0.0073	0.0049	0.0108	0.0089	0.0095	0.0050	0.0367	0.0016	0.0018	0.0222	0.0169	0.0030
SP2	0.1418	0.0485	0.1039	0.1304	0.0576	0.0007	0.0004	0.0001	0.0038	0.0019	0.0036	0.0027	0.0034	0.0011	0.0074	0.0018	0.0019	0.0240	0.0194	0.0022
SP3	0.1887	0.1619	0.0903	0.2988	0.1873	0.0003	0.0001	0.0000	0.0017	0.0010	0.0022	0.0018	0.0019	0.0009	0.0068	0.0005	0.0005	0.0066	0.0052	0.0008
SP4	0.2191	0.2303	0.1737	0.0920	0.0532	0.0004	0.0001	0.0001	0.0020	0.0012	0.0026	0.0021	0.0023	0.0011	0.0080	0.0006	0.0007	0.0086	0.0067	0.0010
SP5	0.2373	0.1695	0.2225	0.3125	0.0578	0.0004	0.0001	0.0000	0.0020	0.0013	0.0027	0.0022	0.0024	0.0012	0.0084	0.0006	0.0006	0.0076	0.0060	0.0009
CU1	0.0148	0.0063	0.0054	0.0039	0.0021	0.0181	0.0341	0.0258	0.0836	0.0846	0.0742	0.0635	0.0462	0.0196	0.1394	0.0330	0.1848	0.1129	0.0949	0.0439
CU2	0.0025	0.0027	0.0017	0.0010	0.0005	0.0049	0.0002	0.0184	0.0300	0.0106	0.0261	0.0194	0.0476	0.0088	0.0653	0.0002	0.0010	0.0012	0.0018	0.0067
CU3	0.0023	0.0025	0.0016	0.0009	0.0005	0.0043	0.0002	0.0001	0.0273	0.0075	0.0194	0.0129	0.0484	0.0046	0.0330	0.0002	0.0009	0.0014	0.0019	0.0108
CU4	0.0565	0.0432	0.0452	0.0223	0.0125	0.1618	0.0055	0.0041	0.0891	0.1671	0.2583	0.2548	0.1104	0.0233	0.1446	0.0056	0.0298	0.0229	0.0203	0.0554
CU5	0.0153	0.0116	0.0113	0.0058	0.0032	0.1145	0.0039	0.0029	0.2226	0.0646	0.2721	0.2105	0.0801	0.0270	0.1723	0.0040	0.0211	0.0164	0.0144	0.0570
EP1	0.0188	0.0110	0.0141	0.0069	0.0039	0.0289	0.0010	0.0007	0.1598	0.0898	0.0987	0.2144	0.0581	0.0476	0.2158	0.0011	0.0054	0.0048	0.0048	0.0152
EP2	0.0070	0.0060	0.0053	0.0028	0.0015	0.0198	0.0007	0.0005	0.1032	0.0724	0.1279	0.0688	0.0464	0.0254	0.1807	0.0007	0.0037	0.0032	0.0034	0.0113
EP3	0.0236	0.0327	0.0129	0.0091	0.0047	0.0152	0.0008	0.0005	0.0838	0.0473	0.2223	0.0801	0.0522	0.0308	0.2082	0.0020	0.0042	0.0134	0.0300	0.1193
EP4	0.0056	0.0324	0.0041	0.0044	0.0020	0.0031	0.0001	0.0001	0.0155	0.0125	0.0295	0.0251	0.0252	0.0153	0.1153	0.0002	0.0007	0.0014	0.0016	0.0038
EP5	0.0148	0.0174	0.0103	0.0060	0.0032	0.0306	0.0011	0.0008	0.1532	0.1232	0.2921	0.2486	0.2497	0.1513	0.1433	0.0014	0.0060	0.0070	0.0101	0.0371
ME1	0.0025	0.0024	0.0018	0.0010	0.0005	0.0070	0.1842	0.0699	0.0355	0.0270	0.0282	0.0231	0.0273	0.0095	0.0693	0.0049	0.0353	0.0900	0.0180	0.0117
ME2	0.0035	0.0036	0.0025	0.0014	0.0008	0.0091	0.0108	0.0011	0.0438	0.0399	0.0553	0.0452	0.0462	0.0228	0.1665	0.0107	0.0122	0.1597	0.0959	0.0191
ME3	0.0028	0.0028	0.0020	0.0011	0.0006	0.0068	0.0105	0.0039	0.0378	0.0207	0.0378	0.0292	0.0352	0.0127	0.0875	0.0539	0.0562	0.0428	0.1719	0.0789
ME4	0.0105	0.0093	0.0078	0.0041	0.0023	0.0268	0.0088	0.0036	0.1583	0.0661	0.1079	0.0739	0.1093	0.0162	0.0708	0.0422	0.0456	0.1689	0.0348	0.0313
ME5	0.0004	0.0003	0.0003	0.0001	0.0001	0.0009	0.0007	0.0003	0.0055	0.0025	0.0043	0.0031	0.0042	0.0010	0.0061	0.0037	0.0039	0.0583	0.0317	0.0048

Table A3. The weighted supermatrix for indicators.

	SP1	SP2	SP3	SP4	SP5	CU1	CU2	CU3	CU4	CU5	EP1	EP2	EP3	EP4	EP5	ME1	ME2	ME3	ME4	ME5
SP1	0.0735	0.1668	0.1697	0.1824	0.2148	0.0031	0.0013	0.0011	0.0058	0.0058	0.0065	0.0064	0.0095	0.0117	0.0195	0.0095	0.0044	0.0286	0.0286	0.0058
SP2	0.1358	0.0509	0.1203	0.1179	0.1146	0.0015	0.0013	0.0010	0.0030	0.0023	0.0021	0.0019	0.0034	0.0026	0.0039	0.0104	0.0045	0.0310	0.0329	0.0044
SP3	0.1806	0.1698	0.1046	0.2701	0.3729	0.0007	0.0004	0.0003	0.0013	0.0012	0.0013	0.0013	0.0019	0.0022	0.0036	0.0029	0.0013	0.0086	0.0088	0.0015
SP4	0.2097	0.2415	0.2012	0.0832	0.1060	0.0008	0.0005	0.0004	0.0016	0.0015	0.0016	0.0015	0.0023	0.0026	0.0042	0.0037	0.0016	0.0111	0.0114	0.0019
SP5	0.2272	0.1778	0.2578	0.2824	0.1151	0.0008	0.0004	0.0004	0.0016	0.0015	0.0016	0.0016	0.0024	0.0027	0.0045	0.0033	0.0015	0.0099	0.0101	0.0018
CU1	0.0141	0.0067	0.0063	0.0035	0.0042	0.0398	0.1292	0.1936	0.0661	0.1000	0.0443	0.0457	0.0459	0.0462	0.0740	0.1953	0.4441	0.1461	0.1609	0.0853
CU2	0.0024	0.0028	0.0020	0.0009	0.0011	0.0108	0.0007	0.1383	0.0237	0.0125	0.0156	0.0139	0.0473	0.0207	0.0346	0.0014	0.0023	0.0015	0.0031	0.0130
CU3	0.0022	0.0026	0.0018	0.0008	0.0010	0.0095	0.0006	0.0009	0.0216	0.0088	0.0116	0.0093	0.0481	0.0108	0.0175	0.0014	0.0021	0.0018	0.0032	0.0209
CU4	0.0541	0.0453	0.0524	0.0202	0.0249	0.3555	0.0208	0.0310	0.0704	0.1975	0.1541	0.1833	0.1097	0.0548	0.0767	0.0334	0.0715	0.0296	0.0345	0.1076
CU5	0.0147	0.0122	0.0131	0.0053	0.0064	0.2517	0.0147	0.0219	0.1759	0.0764	0.1623	0.1514	0.0796	0.0636	0.0914	0.0237	0.0507	0.0213	0.0244	0.1108
EP1	0.0180	0.0115	0.0163	0.0063	0.0078	0.0635	0.0038	0.0056	0.1262	0.1061	0.0589	0.1542	0.0577	0.1120	0.1144	0.0064	0.0129	0.0061	0.0082	0.0295
EP2	0.0067	0.0063	0.0062	0.0025	0.0030	0.0435	0.0026	0.0038	0.0815	0.0856	0.0763	0.0495	0.0461	0.0598	0.0958	0.0044	0.0089	0.0041	0.0058	0.0220
EP3	0.0226	0.0343	0.0150	0.0082	0.0094	0.0334	0.0030	0.0037	0.0662	0.0559	0.1327	0.0576	0.0519	0.0724	0.1104	0.0116	0.0101	0.0174	0.0509	0.2320
EP4	0.0054	0.0340	0.0047	0.0040	0.0040	0.0068	0.0005	0.0006	0.0123	0.0147	0.0176	0.0181	0.0251	0.0359	0.0612	0.0011	0.0016	0.0018	0.0027	0.0074
EP5	0.0142	0.0183	0.0119	0.0054	0.0064	0.0673	0.0042	0.0060	0.1210	0.1456	0.1743	0.1788	0.2482	0.3559	0.0760	0.0083	0.0143	0.0090	0.0172	0.0722
ME1	0.0024	0.0025	0.0021	0.0009	0.0011	0.0153	0.6988	0.5250	0.0280	0.0319	0.0168	0.0166	0.0271	0.0222	0.0368	0.0290	0.0848	0.1164	0.0305	0.0228
ME2	0.0033	0.0038	0.0029	0.0013	0.0015	0.0201	0.0411	0.0084	0.0346	0.0472	0.0330	0.0325	0.0460	0.0535	0.0883	0.0634	0.0294	0.2065	0.1626	0.0372
ME3	0.0027	0.0029	0.0024	0.0010	0.0012	0.0149	0.0399	0.0293	0.0299	0.0245	0.0226	0.0210	0.0350	0.0299	0.0464	0.3190	0.1350	0.0553	0.2915	0.1535
ME4	0.0100	0.0098	0.0090	0.0037	0.0045	0.0589	0.0334	0.0267	0.1251	0.0781	0.0644	0.0532	0.1086	0.0382	0.0376	0.2497	0.1096	0.2185	0.0590	0.0609
ME5	0.0004	0.0004	0.0003	0.0001	0.0002	0.0021	0.0028	0.0021	0.0043	0.0030	0.0026	0.0023	0.0042	0.0024	0.0033	0.0222	0.0095	0.0754	0.0537	0.0094

Table A4. The limited supermatrix for indicators.

	SP1	SP2	SP3	SP4	SP5	CU1	CU2	CU3	CU4	CU5	EP1	EP2	EP3	EP4	EP5	ME1	ME2	ME3	ME4	ME5
SP1	0.0396	0.0396	0.0396	0.0396	0.0396	0.0396	0.0396	0.0396	0.0396	0.0396	0.0396	0.0396	0.0396	0.0396	0.0396	0.0396	0.0396	0.0396	0.0396	0.0396
SP2	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278
SP3	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439
SP4	0.0342	0.0342	0.0342	0.0342	0.0342	0.0342	0.0342	0.0342	0.0342	0.0342	0.0342	0.0342	0.0342	0.0342	0.0342	0.0342	0.0342	0.0342	0.0342	0.0342
SP5	0.0426	0.0426	0.0426	0.0426	0.0426	0.0426	0.0426	0.0426	0.0426	0.0426	0.0426	0.0426	0.0426	0.0426	0.0426	0.0426	0.0426	0.0426	0.0426	0.0426
CU1	0.0950	0.0950	0.0950	0.0950	0.0950	0.0950	0.0950	0.0950	0.0950	0.0950	0.0950	0.0950	0.0950	0.0950	0.0950	0.0950	0.0950	0.0950	0.0950	0.0950
CU2	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139
CU3	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101
CU4	0.1065	0.1065	0.1065	0.1065	0.1065	0.1065	0.1065	0.1065	0.1065	0.1065	0.1065	0.1065	0.1065	0.1065	0.1065	0.1065	0.1065	0.1065	0.1065	0.1065
CU5	0.0876	0.0876	0.0876	0.0876	0.0876	0.0876	0.0876	0.0876	0.0876	0.0876	0.0876	0.0876	0.0876	0.0876	0.0876	0.0876	0.0876	0.0876	0.0876	0.0876
EP1	0.0565	0.0565	0.0565	0.0565	0.0565	0.0565	0.0565	0.0565	0.0565	0.0565	0.0565	0.0565	0.0565	0.0565	0.0565	0.0565	0.0565	0.0565	0.0565	0.0565
EP2	0.0399	0.0399	0.0399	0.0399	0.0399	0.0399	0.0399	0.0399	0.0399	0.0399	0.0399	0.0399	0.0399	0.0399	0.0399	0.0399	0.0399	0.0399	0.0399	0.0399
EP3	0.0497	0.0497	0.0497	0.0497	0.0497	0.0497	0.0497	0.0497	0.0497	0.0497	0.0497	0.0497	0.0497	0.0497	0.0497	0.0497	0.0497	0.0497	0.0497	0.0497
EP4	0.0138	0.0138	0.0138	0.0138	0.0138	0.0138	0.0138	0.0138	0.0138	0.0138	0.0138	0.0138	0.0138	0.0138	0.0138	0.0138	0.0138	0.0138	0.0138	0.0138
EP5	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785	0.0785
ME1	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452
ME2	0.0558	0.0558	0.0558	0.0558	0.0558	0.0558	0.0558	0.0558	0.0558	0.0558	0.0558	0.0558	0.0558	0.0558	0.0558	0.0558	0.0558	0.0558	0.0558	0.0558
ME3	0.0668	0.0668	0.0668	0.0668	0.0668	0.0668	0.0668	0.0668	0.0668	0.0668	0.0668	0.0668	0.0668	0.0668	0.0668	0.0668	0.0668	0.0668	0.0668	0.0668
ME4	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800
ME5	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127	0.0127

Table A5. Collected data from underground gold mines.

	SP1	SP2	SP3	SP4	SP5	CU1	CU2	CU3	CU4	CU5	EP1	EP2	EP3	EP4	EP5	ME1	ME2	ME3	ME4	ME5
M1	0.00	6.00	0.00	100.00	2.20	93.10	94.96	100.00	65.14	100.00	100.00	100.00	100.00	100.00	0.60	3.47	6.90	118.85	8.34	22.11
M2	0.00	7.00	0.00	100.00	1.15	95.79	95.13	71.46	84.30	100.00	67.90	100.00	100.00	100.00	1.28	4.25	4.21	19.76	9.80	47.03
M3	0.00	0.00	0.00	100.00	3.20	95.52	92.52	60.00	94.93	100.00	20.00	100.00	100.00	100.00	2.00	4.00	4.00	141.58	9.45	28.50
M4	0.00	1.00	0.00	100.00	4.95	93.62	96.50	72.63	0.00	100.00	100.00	100.00	100.00	100.00	1.42	12.00	6.38	22.38	5.38	24.58
M5	0.00	0.00	0.00	100.00	1.45	96.44	95.95	83.32	5.33	100.00	38.53	97.00	100.00	100.00	3.10	13.95	1.44	56.30	4.13	8.83
M6	0.00	0.00	0.00	100.00	4.10	89.55	85.00	81.71	30.00	100.00	20.00	99.00	99.00	98.00	1.00	10.08	10.45	41.42	5.75	108.81

Table A6. The normalized evaluation matrix.

	SP1	SP2	SP3	SP4	SP5	CU1	CU2	CU3	CU4	CU5	EP1	EP2	EP3	EP4	EP5	ME1	ME2	ME3	ME4	ME5
M1	1.0000	0.5385	1.0000	1.0000	0.4444	0.9654	0.9840	1.0000	0.6862	1.0000	1.0000	1.0000	1.0000	1.0000	0.1935	1.0000	0.2087	0.8395	0.8510	0.3994
M2	1.0000	0.5000	1.0000	1.0000	0.2319	0.9933	0.9858	0.7146	0.8880	1.0000	0.6790	1.0000	1.0000	1.0000	0.4134	0.8165	0.3420	0.1395	1.0000	0.1878
M3	1.0000	1.0000	1.0000	1.0000	0.6465	0.9905	0.9588	0.6000	1.0000	1.0000	0.2000	1.0000	1.0000	1.0000	0.6452	0.8675	0.3600	1.0000	0.9643	0.3098
M4	1.0000	0.8750	1.0000	1.0000	1.0000	0.9708	1.0000	0.7263	0.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.4581	0.2892	0.2257	0.1581	0.5490	0.3592
M5	1.0000	1.0000	1.0000	1.0000	0.2929	1.0000	0.9943	0.8332	0.0561	1.0000	0.3853	0.9700	1.0000	1.0000	1.0000	0.2487	1.0000	0.3977	0.4214	1.0000
M6	1.0000	1.0000	1.0000	1.0000	0.8283	0.9286	0.8808	0.8171	0.3160	1.0000	0.2000	0.9900	0.9900	0.9800	0.3226	0.3442	0.1378	0.2926	0.5867	0.0812

Table A7. The weighted normalized evaluation matrix.

	SP1	SP2	SP3	SP4	SP5	CU1	CU2	CU3	CU4	CU5	EP1	EP2	EP3	EP4	EP5	ME1	ME2	ME3	ME4	ME5	Scores
M1	0.0396	0.0150	0.0439	0.0342	0.0189	0.0917	0.0137	0.0101	0.0731	0.0876	0.0565	0.0399	0.0497	0.0138	0.0152	0.0452	0.0116	0.0561	0.0681	0.0051	0.7889
M2	0.0396	0.0139	0.0439	0.0342	0.0099	0.0944	0.0137	0.0072	0.0946	0.0876	0.0384	0.0399	0.0497	0.0138	0.0324	0.0369	0.0191	0.0093	0.0800	0.0024	0.7608
M3	0.0396	0.0278	0.0439	0.0342	0.0275	0.0941	0.0133	0.0060	0.1065	0.0876	0.0113	0.0399	0.0497	0.0138	0.0506	0.0392	0.0201	0.0668	0.0772	0.0039	0.8531
M4	0.0396	0.0244	0.0439	0.0342	0.0426	0.0922	0.0139	0.0073	0.0000	0.0876	0.0565	0.0399	0.0497	0.0138	0.0359	0.0131	0.0126	0.0106	0.0439	0.0046	0.6662
M5	0.0396	0.0278	0.0439	0.0342	0.0125	0.0950	0.0138	0.0084	0.0060	0.0876	0.0218	0.0387	0.0497	0.0138	0.0785	0.0113	0.0558	0.0266	0.0337	0.0127	0.7112
M6	0.0396	0.0278	0.0439	0.0342	0.0353	0.0882	0.0122	0.0082	0.0337	0.0876	0.0113	0.0395	0.0492	0.0135	0.0253	0.0156	0.0077	0.0195	0.0469	0.0010	0.6403

Table A8. Potential improvements for underground gold mines.

	SP1	SP2	SP3	SP4	SP5	CU1	CU2	CU3	CU4	CU5	EP1	EP2	EP3	EP4	EP5	ME1	ME2	ME3	ME4	ME5
M1		✓			✓										✓	✓				
M2		✓			✓			✓								✓		✓		
M3								✓			✓					✓				
M4								✓	✓									✓	✓	
M5					✓				✓		✓	✓					✓		✓	✓
M6						✓	✓		✓		✓		✓	✓	✓				✓	

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