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Determining the Appropriate Rehabilitation Method in Open-Pit mines using Decision-Making Methods: A Case Study of the Zarshuran Gold Mine

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Abstract

Open-pit mine rehabilitation is essential for managing environmental impacts and achieving sustainable development after mining operations cease. The goal of this study is to find the best way to fix up the Zarshuran Gold Mine by ranking eight different ways to fix it up using the Fuzzy Analytic Hierarchy Process (FAHP). These options are restoring the mine to its original state, planting trees, building a wind farm, creating a recreational area, setting up pastures, farming, building a solar power plant, and creating a tourist attraction. A panel of twelve experts evaluated these alternatives according to ten key criteria: air temperature intensity, number of sunny days, soil conditions, distance from residential areas, topographic irregularity, vegetation density, average wind speed, local animal species, site access, and the size and shape of the mined area. The results indicate that the construction of a solar power plant is identified as the most suitable rehabilitation option for the Zarshuran Gold Mine, considering the region's climatic conditions (particularly the high number of sunny days per year) and its potential for clean energy generation and revenue creation. This study emphasizes the importance of considering environmental, social, and technical criteria in the decision-making process for mine rehabilitation and provides a framework for selecting sustainable rehabilitation methods in similar mining contexts.

1. Introduction

Today's world economy is completely dependent on energy, and it is considered impossible to imagine its continuation without mining. On the other hand, the preservation of life on Earth cannot be ensured without the establishment of laws and restrictions that regulate the effects of mining and support the environment. The integration of semi-quantitative assessment models with strategic management is increasingly being recognized as crucial in the mineral sector to address these challenges [1]. In this regard, the only way to converge these two seemingly contradictory goals, ensuring that, first, the energy and mineral supply chain, which serves as the foundation for production and construction in societies, remains intact, and second, that this process does not lead to long-term environmental degradation and human problems, is through mine completion and rehabilitation operations. Since the late 20th century, a growing body of research has been conducted on sustainable development in mining, aiming to balance economic, social, and environmental factors [2].

The need for mine reclamation has been derived from the understanding that the extraction and handling of mined resources, if not safely and consistently reintegrated into the natural ecosystem via suitable reclamation techniques, would pose significant risks. For open-pit operations, reclamation must be carried out with careful consideration of environmental, technical, and socio-economic dimensions to achieve sustainable

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development and mitigate long-term environmental impacts [3]. The effective rehabilitation of mining areas, especially in environmentally sensitive regions, requires comprehensive assessments of environmental and socio-economic criteria to ensure the sustainability of post-mining land use [4]. The spread of pollution, destruction of the region's ecosystem, formation of cliffs, contamination of water resources, and other environmental concerns are among the challenges posed. Soil contamination by heavy metals has been identified as a significant concern, as it may occur through both natural processes and human activities such as mining. Heavy metals, including lead and cadmium, are released into the environment, affecting soil quality and potentially entering the food chain [5]. Phytoremediation, which involves the use of plants for heavy metal removal from the soil, is being developed as a sustainable solution [5, 6]. This approach has also been found to contribute to the prevention of oral diseases caused by heavy metals [6]. In mining areas, the destruction of natural structures such as gravel layers and vegetation leads to increased soil erosion, reduced water quality, and accelerated desertification, highlighting the necessity of careful planning in rehabilitation and restoration efforts [7]. Although mine rehabilitation cannot entirely neutralize the harmful effects of mining on the environment, it is regarded as the most effective tool for offsetting these impacts [8].

Mine rehabilitation is considered essential for mitigating environmental impacts, restoring ecosystems, and ensuring sustainable land use, as it facilitates the transformation of degraded areas into functional landscapes long after mining ceases [9, 10]. Decision-making regarding the use of areas affected by mining has been recognized as an integral component of the mine life cycle, with the precision and accuracy of such decisions having significant long-term consequences for the ecosystem of the mined area as well as its surroundings. The continuation of the mine life is generally categorized into one of four options: restoration to its original state, mine rehabilitation, establishment of alternative ecosystems, or abandonment. A careful decision-making process and the selection of an optimal method are required, as they directly reduce the overall costs of mining operations while ensuring long-term and safe land use through the adaptation of the restoration method to site-specific conditions. Multi-criteria decision-making methods are increasingly being employed in the mining industry for sustainable decision-making, particularly in the context of mine rehabilitation [11].

A ranking of rehabilitation options was conducted by Gholianzadeh et al. based on the Ideal Solution Similarity Method (TOPSIS), which is recognized as one of the multi-criteria decision-making tools, to determine a suitable rehabilitation approach for the tailings dam of an open-pit mine. The model was applied to a hypothetical mine characterized by moderate to cold mountainous climatic conditions, short warm periods, long cold periods, low rainfall, high snowfall, and acid-generating tailings [12]. In a separate study, an AHP-based model was used by Baştin to select the optimal reclamation method for an open-pit coal mine located in the Seyitomer region of western Turkey. The findings of the proposed model indicated that it could be utilized to enhance group decision-making in selecting a reclamation method that meets optimal specifications. The mine, which contains 200 million tons of lignite reserves, extends 8,500 meters in length and 4,200 meters in width, with an overburden thickness ranging from 35 to 60 meters, mined in three to six steps at heights of 10 meters. Five rehabilitation options were proposed for the mine, including agriculture, afforestation/forest land, recreational development, large-scale residential development, and new community residential development systems. Technical parameters of the mine, as well as soil parameters such as porosity, pH, carbonate, and nitrogen levels, were measured for this case [13]. In another study, a multi-criteria decision-making technique named PROMETHEE was used by Soltanmohammadi et al. to determine the priority ranking of post-mining land uses through the MLSA framework [14]. Bangiyan et al. developed a pit mine rehabilitation approach based on two innovative concepts. The first concept involved the development of a model that considers the diversity among different extracted land sections and establishes effective criteria to define the optimal rehabilitation method for each section. The second concept employed fuzzy sets and fuzzy numbers due to the inherent uncertainty in influential parameters [15]. The Delphi fuzzy multi-criteria decision-making technique was used by Haj Kazemiha et al. to prioritize criteria [16].

Subsequently, different decision-making models have been utilized by researchers such as Alavi [17], Zimmerman [18], Anis et al. [19], Mozafari [20], and Sitorus et al. [21] to select the best option under different criteria. Moreover, the development of ecological literacy within mining communities has been emphasized as crucial for fostering a perspective of sustainable development [22]. The establishment of models aimed at reducing the risk of premature mine closure has also been identified as essential for ensuring long-term sustainability [23]. In this context, the fuzzy AHP method was employed, involving the selection of 10 criteria and 8 options structured in a questionnaire for the study group. The application of multi-criteria decision-making systems spans multiple fields of knowledge, with the experience and technical expertise of the expert group contributing significantly to the accuracy and effectiveness of the method. Accordingly, the target expert group was categorized into three groups: university professors with relevant expertise, mining professionals with substantial experience in mining activities, and officials and managers from the studied mine. Upon distribution of the questionnaires, experts were asked to assign appropriate scores to each proposed criterion based on their scientific and practical knowledge. The accuracy of the responses was subsequently reviewed and verified. Based on the collected data, the optimal rehabilitation option for the study area was determined using the fuzzy AHP method. The role of corporate social responsibility has been highlighted as vital in the context of complex mining systems, aligning with the principles of sustainable development [24].

Previous studies on open-pit mine rehabilitation have employed multi-criteria decision-making methods to select optimal options. However, certain limitations are evident in these studies. Many have focused on a narrow set of environmental, social, and economic factors, often addressing only one or two aspects rather than integrating all relevant dimensions. Additionally, in some cases, the evaluation of criteria has been conducted using classical methods, which lack the ability to model uncertainty effectively.

In this research, these limitations have been mitigated using the FAHP method and the integration of ten key criteria. Incorporating expert opinions from various fields and applying a fuzzy approach have enhanced the accuracy and comprehensiveness of the decision-making process for selecting the most suitable rehabilitation method for the Zarshuran mine.

2. Materials & Methodology

Various theories and methods have been proposed for decision-making in researchers' problems, but since the industrial revolution in the world and especially since World War II, optimization models have been of interest to many mathematicians and industry executives. The main emphasis on classical optimization models is to have a criterion (or an objective function) so that the model can be linear, nonlinear, or mixed in total; but in recent decades, researchers' attention has been focused on multi-criteria models for evaluating complex decisions [25]. Multi-criteria decision-making methods are divided into two categories: multi-objective decision-making and multi-attribute decision-making. The goal of decision-making is to select the best option or weigh the decision-making factors. Each decision-making method has a specific task; one of the methods aims to weight the criteria, another aims to rank the options, and another aims to evaluate the criteria. A classification of multi-criteria decision-making models is presented in Figure 1 [26].

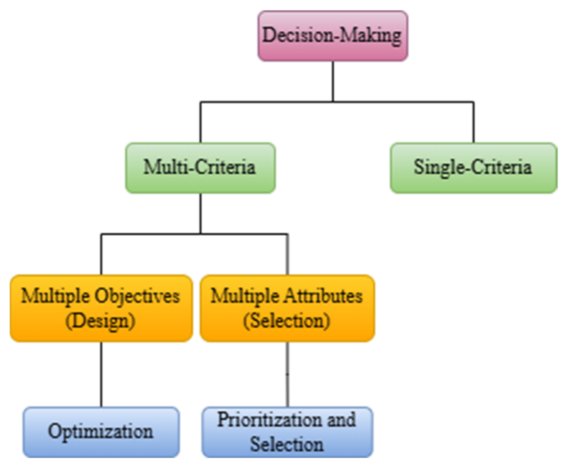


Figure 1. Classification of multi-criteria decision-making models

In a different instance, multi-criteria decision-making models may be divided into two major categories: compensatory and non-compensatory ones (Figure 2). Within compensatory models, the decision maker is willing to trade off between different criteria and indicators. A change in one indicator is compensated for by an offsetting change in another indicator or indicators; by contrast, the decision maker within non-compensatory models has no such propensity to trade off between the criteria. The weaknesses of one indicator are not compensated for by the strengths of another indicator. Each indicator is used in isolation from the others to evaluate alternative options [27].

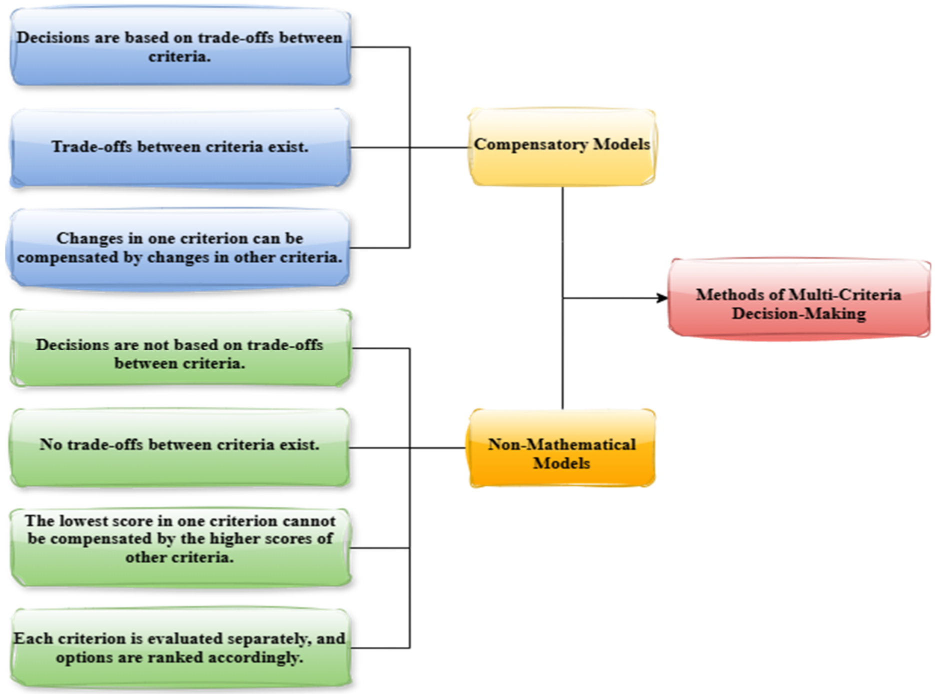


Figure 1. Classification of multi-criteria decision-making methods

In this study, compensatory methods have been investigated due to their use. Compensatory methods are divided into three categories: scoring methods, compromise methods, and non-ranking methods (Figure 3).

Scoring methods: The preferred option has the highest score. In these methods, using different algorithms, the superior option is the one that obtains the highest score.

Compromising methods: The preferred option has the highest proximity and similarity to the ideal option.

Outranking methods: The preferred option has the best situation from the perspective of a defined coordinated index [25].

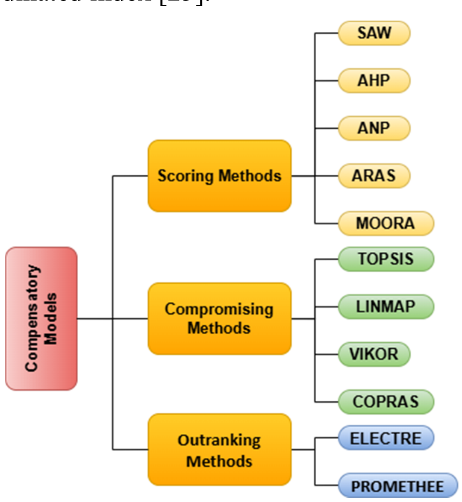


Figure 2. Classification of compensatory methods

2.1. Analytical Hierarchy Process

This technique is a powerful and flexible method in the category of multi-criteria decision-making methods that can solve complex problems at different levels. For this reason, it is called a hierarchy model because it is presented in the form of a tree and ordered model. The AHP method combines both objective and subjective evaluations in an integrated structure based on paired comparison scales and helps analysts organize the essential aspects of a problem in a hierarchical format. Among the advantages of this method are measuring the consistency of decision-makers' judgments, creating pairwise comparisons in choosing the optimal solution and option, the ability to consider criteria and sub-criteria in evaluating options, and creating the ability to achieve the best option through pairwise comparisons [26].

2.2. Fuzzy Analytical Hierarchy Process (Fuzzy AHP)

The Necessity of Fuzzy Analytical Hierarchy Process (Fuzzy AHP): The AHP method has been widely used for selecting an option among various alternatives. However, in this method, pairwise comparisons for each level are performed using a nine-point scale to select the best option according to the goal [20]. Thus, the application of AHP has some shortcomings, such as:

- AHP is essentially used in crisp decision-making.
- It examines judgments using an extremely imbalanced scale.
- It does not account for the uncertainties present in individual judgments.
- The ranking method in AHP is relatively imprecise.
- Subjective judgments, as well as the selection and performance of decision-makers, significantly influence AHP results.

Moreover, it is widely accepted that individuals' assessments of qualitative criteria are always subjective and thus imprecise. Therefore, conventional and classical AHP seem insufficient and inefficient for meeting decision-makers' precise requirements.

To model such uncertainties in human preferences, fuzzy set theory should be integrated with pairwise comparisons as an extension of the AHP technique. This combined decision-making technique provides a more accurate understanding of the decision-making process.

AHP is a tool for multi-criteria decision-making that can structure complex problems hierarchically, simplifying the evaluation of all criteria relevant to the decision. All alternatives are compared separately for each criterion using a preference scale, and a priority list of alternatives for each criterion is obtained. The most commonly used preference scale is the 1-9 scale.

Fuzzy AHP enables decision-makers to assign more realistic scores to alternatives in scenarios with many uncertainties. Chang's Extent Analysis model (1992) is one such approach, which depends on the degree of probability for each criterion [27]. Triangular fuzzy numbers (l, m, u) are used to create the pairwise comparison scale, and a pairwise comparison matrix is constructed for each level in the hierarchy. Then, the subsets of each row in the matrix are calculated to form a new set. Membership functions, which represent the average weight corresponding to the alternatives in the relevant matrix, are calculated for each criterion using these values.

To apply the process based on this hierarchy, according to Chang's extent analysis method (1992), each criterion is considered, and for each criterion, the criterion gig_igi is measured. The fuzzy analytical hierarchy process (Fuzzy AHP) is used for weighting and ranking the criteria or alternatives in the study.

There are three methods for calculating weights in the Fuzzy AHP method:

1. The Chang's extent analysis method.
2. The improved Fuzzy AHP method.
3. The Mikhailov fuzzy prioritization method.

In this study, the Fuzzy AHP method is explained based on Chang's extent analysis approach.

Step 1) Forming the Hierarchical Research Model:

In this step, after identifying the criteria, sub-criteria, and alternatives of the research, the hierarchical research model must be determined.

Step 2) Creating Pairwise Comparison Tables and Responding:

In this step, similar to the AHP method, pairwise comparisons must be created, and these comparisons are responded to using the fuzzy scale below. This is the 9-point fuzzy AHP scale. Although 5-point or 7-point scales can also be used, the 9-point scale is a standard scale.

Step 3) Calculating the Consistency Ratio of Pairwise Comparisons:

In this step, the consistency ratio of the pairwise comparisons must be examined. If this ratio is less than 0.1, it indicates that the pairwise comparison is sufficiently stable and consistent. The consistency ratio in fuzzy matrices can be calculated in two ways: first, defuzzify the fuzzy pairwise comparison matrix and then calculate its inconsistency rate definitively, or calculate it using the Gauss and Boucher method of calculating the inconsistency rate.

Step 4) Combining Pairwise Comparisons:

When multiple respondents have provided answers to pairwise comparisons, the geometric mean method is used to combine them, resulting in a merged pairwise comparison matrix. To merge fuzzy matrices, the first entries of all comparisons are averaged geometrically, the second entries are also averaged geometrically, and the third entries are likewise.

Step 5) Calculating Weights Using the Chang's Extent Analysis Method:

Chen and Huang outlined the steps for using the fuzzy TOPSIS method in a multi-criteria decision-making problem with n criteria and m alternatives as follows [21]:

a) Forming the Fuzzy Decision Matrix:

Based on the number of criteria, alternatives, and the evaluation of all alternatives for various criteria, the decision matrix is formed as follows:

$$\widetilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \quad (1)$$

If triangular fuzzy numbers are used, $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$, where $\tilde{x}_{ij}$ represents the performance of the i-th alternative $(i = 1,2,...,m)$ with respect to the j-th criterion $(j = 1,2,...,n)$. However, if trapezoidal fuzzy numbers are used, $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}, d_{ij})$, where $\tilde{x}_{ij}$ represents the performance of the i-th alternative $(i = 1,2,...,m)$ with respect to the j-th criterion $(j = 1,2,...,n)$.

If the decision-making group consists of k members, and the fuzzy ranking of the k-th decision-maker is represented by triangular fuzzy numbers as $\tilde{x}_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk})$, then based on the combined fuzzy ranking criteria $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$, the alternatives can be calculated using equation (2) to (4):

$$a_{ij} = \underset{k}{Min}\{a_{ijk}\} \quad (2)$$

$$b_{ij} = \frac{\sum_{k=1}^{k} b_{ijk}}{k} \quad (3)$$

$$c_{ij} = \underset{k}{Max}\{c_{ijk}\} \quad (4)$$

If the decision-making group has k members, and the fuzzy ranking of the k-th decision-maker is expressed as $\tilde{x}_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk}, d_{ijk})$ based on fuzzy trapezoidal numbers, then the combined fuzzy ranking $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}, d_{ij})$ for the options can be obtained using equation 5 to 8.

$$a_{ij} = \underset{k}{Min}\{a_{ijk}\} \quad (5)$$

$$a_{ij} = \underset{k}{Min}\{a_{ijk}\} \quad (6)$$

$$c_{ij} = \frac{\sum_{k=1}^{k} c_{ijk}}{k} \quad (7)$$

$$d_{ij} = \underset{k}{Max}\{d_{ijk}\} \quad (8)$$

b) Determining the weight matrix of criteria:

At this stage, the importance coefficient of various criteria in decision-making is defined as shown in equation 9.

$$\tilde{w} = [\tilde{w}_1, \tilde{w}_2, ..., \tilde{w}_n] \quad (9)$$

If triangular fuzzy numbers are used, each component of w_j (the weight of the criteria) will be defined as $\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$. However, if trapezoidal fuzzy numbers are used, each component of w_j will be defined as $\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3}, w_{j4})$.

If the decision-making group consists of k members and the fuzzy ranking of the k-th decision-maker is expressed as $\tilde{w}_{jk} = (w_{jk1}, w_{jk2}, w_{jk3},)$ based on triangular fuzzy numbers, then the combined fuzzy ranking of the criteria $\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$ can be obtained using equation 10 to 12.

$$w_{j1} = \underset{k}{Min}\{w_{jk1}\} \quad (10)$$

$$w_{j2} = \frac{\sum_{k=1}^{k} w_{jk2}}{k} \quad (11)$$

$$w_{j3} = \underset{k}{Max}\{w_{jk3}\} \quad (12)$$

If the decision-making group consists of k members and the fuzzy ranking of the k-th decision-maker is expressed as $\tilde{w}_{jk} = (w_{jk1}, w_{jk2}, w_{jk3}, w_{jk4})$ based on trapezoidal fuzzy numbers, then the combined fuzzy ranking of the criteria $\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3}, w_{j4})$ can be obtained using equation 13 to 16.

$$w_{j1} = \underset{k}{Min}\{w_{jk1}\} \quad (13)$$

$$w_{j2} = \frac{\sum_{k=1}^{k} w_{jk2}}{k} \quad (14)$$

$$w_{j3} = \frac{\sum_{k=1}^{k} w_{jk3}}{k} \quad (15)$$

$$w_{j4} = \underset{k}{Max}\{w_{jk4}\} \quad (16)$$

c) Fuzzy Normalization:

When x_{ij} values are fuzzy, the r_{ij} values will also be fuzzy. Instead of complex calculations used in the classical Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method, this stage employs linear scale transformation to convert the scale of various criteria into a comparable scale.

If triangular fuzzy numbers are used, the elements of the normalized decision matrix for positive and negative criteria are calculated using equation 17 and 18, respectively.

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*} \right) \quad (17)$$

$$\tilde{r}_{ij} = \left(\frac{\bar{a}_j}{c_{ij}^*}, \frac{\bar{a}_j}{b_{ij}^*}, \frac{\bar{a}_j}{a_{ij}^*} \right) \quad (18)$$

Where:

$$c_j^* = \max_i c_{ij} \quad (19)$$

$$a_j^- = \min_i a_{ij} \quad (20)$$

But if trapezoidal fuzzy numbers are used, the elements of the scale-free decision matrix for positive and negative criteria are calculated from equations 21 and 22, respectively:

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{d_j^*} . \frac{b_{ij}}{d_j^*} . \frac{c_{ij}}{d_j^*} . \frac{d_{ij}}{d_j^*} \right) \quad (21)$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{d_{ij}} . \frac{a_j^-}{c_{ij}} . \frac{a_j^-}{b_{ij}} . \frac{a_j^-}{a_{ij}} \right) \quad (22)$$

Where:

$$d_j^* = \max_i d_{ij} \quad (23)$$

$$a_j^- = \min_i a_{ij} \quad (24)$$

Therefore, the unscaled fuzzy decision matrix is obtained as equations 25 and 26:

$$\tilde{R} = \begin{bmatrix} \tilde{r}_{11} & \tilde{r}_{12} & \cdots & \tilde{r}_{1n} \\ \tilde{r}_{21} & \tilde{r}_{22} & \cdots & \tilde{r}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{r}_{m1} & \tilde{r}_{m2} & \cdots & \tilde{r}_{mn} \end{bmatrix} \quad (25)$$

$$\tilde{R} = [\tilde{r}_{ij}]_{m \times n} \quad (26)$$

Where m represents the number of options and n represents the number of criteria.

d) Determination of the Weighted Fuzzy Decision Matrix:

Considering the various criteria, the weighted decision matrix is obtained by multiplying the importance weight of each criterion by the normalized fuzzy matrix, as shown in equation 27.

$$\tilde{v}_{ij} = \tilde{r}_{ij} \times \tilde{w}_i \quad (27)$$

Where w_j represents the importance weight of criterion C_j; therefore, the weighted fuzzy decision matrix will be expressed as equation 28 and 29.

$$\tilde{V} = \begin{bmatrix} \tilde{v}_{11} & \tilde{v}_{12} & \cdots & \tilde{v}_{1n} \\ \tilde{v}_{21} & \tilde{v}_{22} & \cdots & \tilde{v}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{v}_{m1} & \tilde{v}_{m2} & \cdots & \tilde{v}_{mn} \end{bmatrix} \quad (28)$$

$$\tilde{V} = [\tilde{v}_{ij}]_{m \times n} \quad (29)$$

If the fuzzy numbers are triangular, the criteria with positive and negative aspects are defined as follows:

$$\tilde{v}_{ij} = \tilde{r}_{ij} \times \tilde{w}_i = \left(\frac{a_{ij}}{c_j^*} . \frac{b_{ij}}{c_j^*} . \frac{c_{ij}}{c_j^*} \right) \times (w_{j1} . w_{j2} . w_{j3}) = \left(\frac{a_{ij}}{c_j^*} \times w_{j1} . \frac{b_{ij}}{c_j^*} \times w_{j2} . \frac{c_{ij}}{c_j^*} \times w_{j3} \right) \quad (30)$$

$$\tilde{v}_{ij} = \tilde{r}_{ij} \times \tilde{w}_i = \left(\frac{a_j^-}{c_{ij}^*} . \frac{a_j^-}{b_{ij}^*} . \frac{a_j^-}{a_{ij}^*} \right) \times (w_{j1} . w_{j2} . w_{j3}) = \left(\frac{a_j^-}{c_{ij}^*} \times w_{j1} . \frac{a_j^-}{b_{ij}^*} \times w_{j2} . \frac{a_j^-}{a_{ij}^*} \times w_{j3} \right) \quad (31)$$

If the fuzzy numbers are trapezoidal, the positive and negative aspects are determined as follows:

$$\tilde{v}_{ij} = \tilde{r}_{ij} \times \tilde{w}_i = \left(\frac{a_{ij}}{d_j^*} . \frac{b_{ij}}{d_j^*} . \frac{c_{ij}}{d_j^*} . \frac{d_{ij}}{d_j^*} \right) \times (w_{j1} . w_{j2} . w_{j3} . w_{j4}) = \left(\frac{a_{ij}}{d_j^*} \times w_{j1} . \frac{b_{ij}}{d_j^*} \times w_{j2} . \frac{c_{ij}}{d_j^*} \times w_{j3} . \frac{d_{ij}}{d_j^*} \times w_{j4} \right) \quad (32)$$

$$\tilde{v}_{ij} = \tilde{r}_{ij} \times \tilde{w}_i = \left(\frac{a_j^-}{d_{ij}} . \frac{a_j^-}{c_{ij}} . \frac{a_j^-}{b_{ij}} . \frac{a_j^-}{a_{ij}} \right) \times (w_{j1} . w_{j2} . w_{j3} . w_{j4}) = \left(\frac{a_j^-}{d_{ij}} \times w_{j1} . \frac{a_j^-}{c_{ij}} \times w_{j2} . \frac{a_j^-}{b_{ij}} \times w_{j3} . \frac{a_j^-}{a_{ij}} \times w_{j4} \right) \quad (33)$$

e) Finding the Fuzzy Ideal and Fuzzy Anti-Ideal Solution:

The fuzzy ideal and fuzzy anti-ideal solutions are obtained using equation 34 and 35, respectively.

$$A^* = \{\tilde{v}_1^*.\tilde{v}_2^*.\cdots.\tilde{v}_n^*\} \quad (34)$$

$$A^- = \{\tilde{v}_1^-.\tilde{v}_2^-.\ldots.\tilde{v}_n^-\} \quad (35)$$

Where the best value i among all options and the worst value of criterion i among all options are determined. These values are obtained from the following equation:

$$\tilde{v}_j^* = \underset{i}{Max}\{\tilde{v}_{ij3}\}.\begin{matrix} i = 1.2.\ldots.m \\ j = 1.2.\ldots.n \end{matrix} \quad (36)$$

$$\tilde{v}_j^- = \underset{i}{Min}\{\tilde{v}_{ij1}\}.\begin{matrix} i = 1.2.\ldots.m \\ j = 1.2.\ldots.n \end{matrix} \quad (37)$$

The options in equations 36 and 37 represent completely better and completely worse options, respectively.

f) Calculating the distance from the fuzzy ideal and anti-ideal solution:

The distance of each alternative from the fuzzy ideal and anti-ideal solution is calculated using the following equations:

$$S_j^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}.\tilde{v}_j^*).\begin{matrix} i = 1.2.\ldots.m \\ j = 1.2.\ldots.n \end{matrix} \quad (38)$$

$$S_j^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}.\tilde{v}_j^-).\begin{matrix} i = 1.2.\ldots.m \\ j = 1.2.\ldots.n \end{matrix} \quad (39)$$

Where is the distance between two fuzzy numbers. If the two fuzzy numbers are triangular, the distance between the two numbers is equal to:

$$d_v(\tilde{M}_1.\tilde{M}_2) = \sqrt{\frac{1}{3}[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2]} \quad (40)$$

If two fuzzy numbers are trapezoidal, the distance between the two numbers is equal to:

$$d_v(\tilde{M}_1.\tilde{M}_2) = \sqrt{\frac{1}{4}[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2 + (d_1 - d_2)^2]} \quad (41)$$

It should be noted that these numbers are definitive.

g) Calculating the Similarity Index

The similarity index is calculated using Equation 42.

$$CC_i = \frac{S_i^-}{S_i^- + S_i^*} \quad (42)$$

h) Ranking the Options

At this stage, based on the similarity index, the options are ranked such that options with higher similarity indices are given higher priority.

3. Case Study

The area of the gold mining project and construction of the Zarshuran gold extraction plant is located 35 kilometers north of the city of Takab in West Azerbaijan Province, 30 kilometers west of Zarshuran, and south of the village of Aghdare.

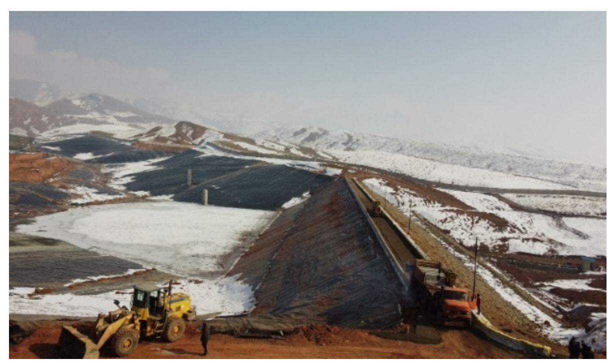


Figure 4. Zarshuran Gold Mine

The average elevation of the deposit above sea level is +2350 meters, the minimum elevation at the confluence of the two streams of the Zarshuran and Bakhir-Bulaghi mines is 2200 meters, and the maximum elevation at the peak of Chaldagh Mountain is +2796 meters. The highest elevation in the Takab region is Mount Balqis, with an elevation of 3332 meters, which is located about 18 kilometers east-southeast of the deposit. Figure 4 shows the geographical location of the Zarshuran gold mine.

3.1. Updating the topographic map of the mining area

Based on the latest survey of the mining areas, the general map of the mine, including the mining steps and access roads to different levels, has been updated, which can be seen in Figure 5. Also, in order to accurately examine the geometry and specifications of the mining steps in design and implementation, the status of the steps is shown in Figure 6. Also, the geometric parameters of the current topography of the mine are included in Table 1.

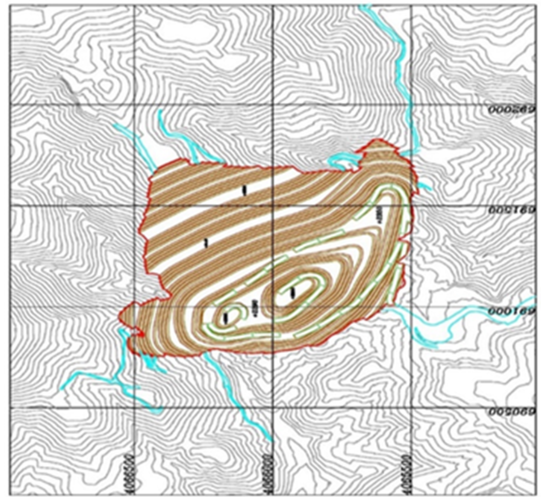
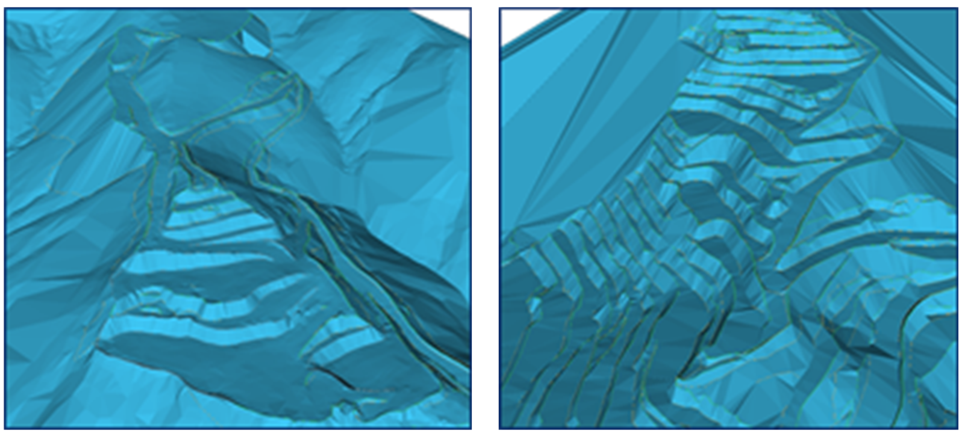


Figure 5. The area of the benches of the Zarshuran mine in topography



(a) **(b)**

Figure 6. Zarshuran mine benches at different levels

Table 1. Geometric parameters of mine topography

Option	Unit	Measure
End level	m	2350
Ground level	m	2720
Mine slope	degree	40-50
Bench witdh	m	10-15

3.2. Updating the geological block model

To conduct studies on the optimization of the final area and mine design, the gold block model was updated. Accordingly, and considering the latest topographic status of the mine steps, the graded block model is shown in Figure 7. Also, the latest topographic status of the mine, access roads, and steps of the Zarshuran mine are shown in Figure 8. The specifications of the graded block model of the Zarshuran ore are listed in Table 2, and the changes in the grade of the elements of the main geological block model are listed in Table 3.

Table 2. Specifications of the Zarshuran ore grade block model

Volume	Tonage	Density	Au	Ag	As	S
m^3	10^3 tons	$\frac{g}{cm^3}$	ppm	ppm	ppm	%
10,973,825	26,032,024	2.38	3.41	6	19,085	3.70

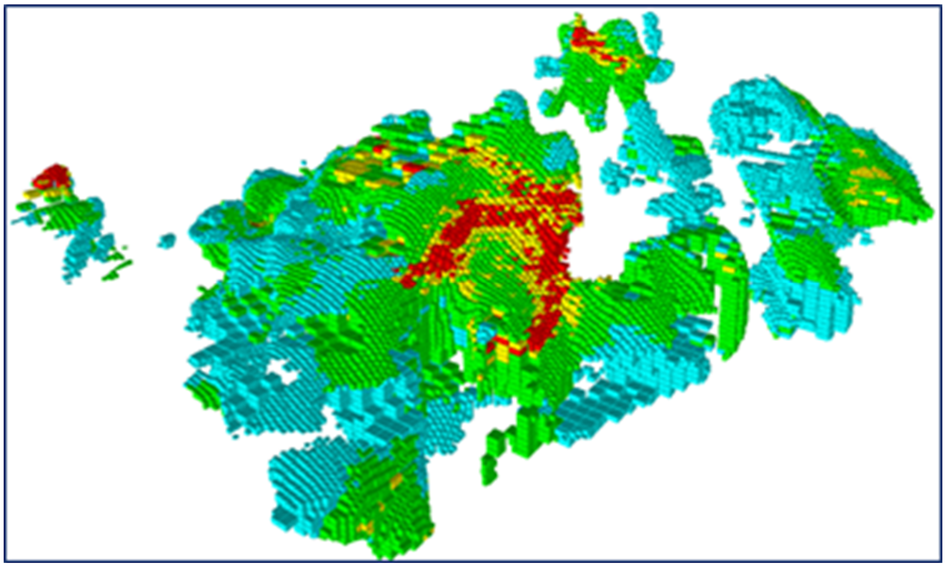


Figure 7. Updated grade block model of the Zarshuran gold mine

Table 3. Modifications in the grade of elements in the main geological block model (Cut-off: 1 ppm)

Type	Unit	Minimum	Maximum	Average
Au	ppm	1	13.17	3.4
Ag	ppm	01	74.99	6.84
As	ppm	3787	153,417.75	20,774
S	%	0785	15.9	3.91

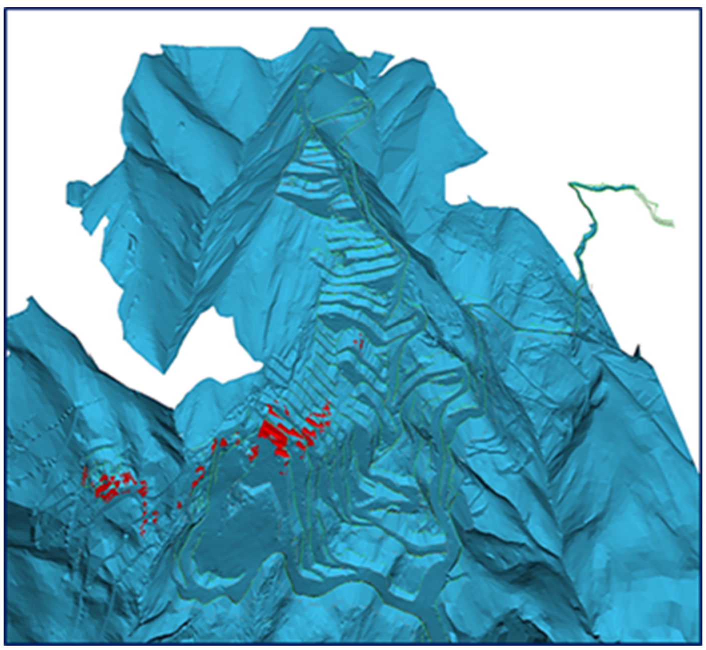


Figure 8. Latest status of the mine topography, access roads and benches of the Zarshuran mine

4. Data Collection and Interpretation

Planning for mine rehabilitation and adopting an appropriate rehabilitation strategy depends on various factors related to the mined land, surrounding environment, mine infrastructure, access roads, and more. Therefore, in this study, experts in this field with several years of experience were asked to identify the most important criteria and strategies for mine rehabilitation. Climatic conditions, general characteristics of the region, ecosystem conditions, and other extraction-related factors were considered the most critical criteria.

Table 4. Characteristics of the Expert Panel Involved in the Survey

Feature	Description
Number of Experts	12
Field of Expertise	Mining Engineering, Environmental Science, Renewable Energy, Project Management
Years of Experience	Between 10 to 25 years of experience in relevant fields
Job Position	University Professor, Mine Manager, Environmental Consultant, Senior Engineer
Education	PhD, Master's degree in relevant fields

In this study, we employ a hybrid approach that integrates Shannon entropy and fuzzy analytic hierarchy process (FAHP) for determining the best rehabilitation method. First, Shannon entropy is used to calculate the objective weights of the criteria based on the distribution of data, thereby reducing the bias that might arise from purely subjective judgments. Next, these entropy-derived weights are incorporated into the FAHP framework, where fuzzy pairwise comparisons by experts provide the final ranking of the alternatives. This synergy captures both the objective (data-driven) perspective from Shannon Entropy and the subjective (expert-based) insight from FAHP, ultimately enhancing the robustness and reliability of the decision-making process.

4.1. Criteria Selection and Justification

The selection of decision-making criteria in this study was based on a comprehensive review of previous studies and expert opinions in the fields of mining and environmental engineering. Criteria such as air temperature, the number of sunny days, and wind speed were included due to their direct impact on renewable energy options like solar and wind power plants. Soil conditions, vegetation cover, and animal species were considered crucial for evaluating options such as agriculture, pastureland, and ecological restoration. Accessibility and distance from residential areas were also included to assess options like recreational and tourism facilities. Additionally, cost, an essential factor in decision-making, was indirectly analyzed through criteria such as financial resources and economic feasibility.

The selection of appropriate criteria is crucial for effective multi-criteria decision-making (MCDM) in mine rehabilitation [11, 29]. This study employs ten criteria (C1-C10) chosen for their relevance to the environmental, social, economic, and technical aspects of post-mining land use at the Zarshuran Gold Mine, aligning with established principles of sustainable mine closure. These criteria ensure a holistic evaluation, considering both site-specific characteristics and broader sustainability goals. The rationale for each criterion is as follows:

- **C1: Air Temperature Intensity (Cold or Hot):** Air temperature significantly impacts revegetation success and the efficiency of renewable energy systems [30]. Extreme temperatures can limit plant growth and reduce photovoltaic panel performance, a critical consideration for the Zarshuran mine, given its location and temperature variations.
- **C2: Number of Sunny Days:** This criterion directly assesses the potential for solar energy generation, a key consideration for sustainable post-mining land use [31]. The Zarshuran mine's reported 312 sunny days per year support the viability of solar power.
- **C3: Soil Conditions Regarding Plant Needs:** Soil quality, including nutrient availability, pH, texture, and contaminant presence, is a primary determinant of successful revegetation [32, 33]. Mining activities often degrade soil, necessitating assessment and remediation to support plant establishment.
- **C4: Distance from the Site to Densely Populated Residential Areas:** This criterion addresses potential social impacts, such as noise, dust, visual intrusion, and health effects, on nearby communities. Minimizing negative impacts is crucial for socially responsible mine closure.
- **C5: Topographic Irregularity:** Topography influences drainage, erosion, slope stability, and land use feasibility [34, 35]. The irregular terrain of open-pit mines often requires extensive earthworks for successful rehabilitation.
- **C6: Vegetation Density in the Area and Surrounding Regions:** Existing vegetation provides a baseline for assessing revegetation potential and ecological restoration. Higher surrounding vegetation density suggests a greater likelihood of successful ecological recovery.
- **C7: Average Wind Speed:** This criterion is essential for evaluating the feasibility of wind energy generation as a post-mining land use [36]. Higher wind speeds indicate greater potential for cost-effective wind power production.
- **C8: Types of Animal Species Around the Area:** Local fauna reflects biodiversity and the potential for habitat restoration. Mine rehabilitation should minimize negative impacts

on wildlife and, where feasible, create habitats that support native species.

- **C9: Access to the Site:** Site accessibility is a crucial logistical factor, influencing the cost, efficiency, and safety of rehabilitation.
- **C10: Size and Shape of the Mined Site**: The physical dimensions and configuration of the mine influence the scale, type, and cost of feasible rehabilitation options.

Although the significance of cost, revenue potential, job creation, and other socio-economic factors in a comprehensive mine rehabilitation plan is fully acknowledged, these criteria were not included in the final analysis for two primary reasons. First, no reliable or sufficiently detailed data were available to estimate the actual costs and financial outcomes of each rehabilitation alternative. Rough estimates would have introduced considerable uncertainty into the model and could have biased the results. Second, the scope of this study was restricted to environmental and technical feasibility based on the available information and the overarching objective of evaluating ecological sustainability. In future research, once more robust economic data become accessible and broader stakeholder engagement is conducted, these economic and social considerations may be incorporated to provide a more holistic decision-making approach.

All the decision-making components of this study are summarized in Table 4.

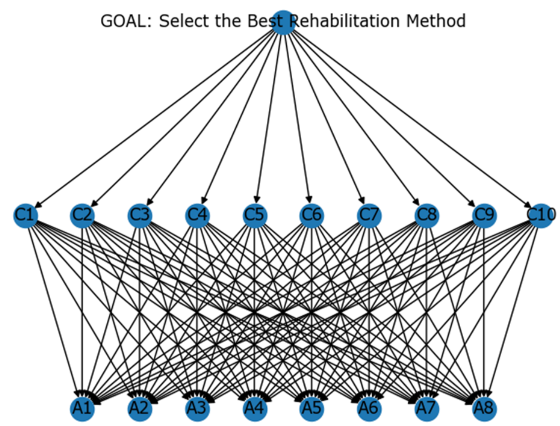


Figure 9. Hierarchical AHP/FAHP Decision Model for Selecting the Best Rehabilitation Method

Table 5. The main components of decision-making for evaluating mine rehabilitation strategies

Strategies		Criteria	
A1	Restoring the land to its original state	**C1**	Air temperature intensity (cold or hot)
A2	Reforestation objectives	**C2**	Number of sunny days
A3	Closing the mine and building wind turbines	**C3**	Soil conditions regarding plant needs
A4	Creating recreational areas and sports facilities	**C4**	Distance from the site to densely populated residential areas
A5	Establishing pasturelands	**C5**	Topographic irregularity
A6	Agricultural objectives	**C6**	Vegetation density in the area and surrounding regions
A7	Mine closure and construction of solar cells	**C7**	Average wind speed
A8	Development of tourist attractions	**C8**	Types of animal species around the area
		C9	Access to the site
		C10	Size and shape of the mined site

In fact, the criteria and options were introduced. Consequently, the mine rehabilitation in this study aims to achieve objectives such as minimizing negative environmental impacts, minimizing negative social impacts, minimizing rehabilitation costs, and maximizing financial income from the rehabilitation strategy. In this study, to fill out the questionnaires, a fuzzy scale was provided to experts in this field, based on which specialized opinions regarding mine rehabilitation options were expressed. This scale is shown in Table 5. As can be seen, a 6-point scale has been prepared for this purpose, with values ranging from 1 to 10. The corresponding verbal variables for the fuzzy numbers range from very low to high.

The evaluation of the proposed criteria and options was based on the opinions of technical office experts and the analysis of similar case studies.

After filling out the questionnaires, the experts' opinions were based on the fuzzy scale. Twelve experts filled out the questionnaires. As shown in Table 6, the experts determined the importance of each criterion for each option based on the defined scale.

Table 6. Fuzzy scale and the fuzzy numbers used

Row	Verbal Variable	Corresponding Fuzzy Number	Abbreviation
1	Very Low	(1, 2, 3)	VL
2	Relatively Low	(2, 3, 4)	L
3	Low	(4, 5, 6)	FL
4	Medium	(5, 6, 7)	M
5	Relatively High	(7, 8, 9)	FH
6	High	(8, 9, 10)	H

Table 7. Expert opinions on mine rehabilitation options

option	(C1)						option	(C2)						option	(C3)					
	VL	L	FL	M	FH	H		VL	L	FL	M	FH	H		VL	L	FL	M	FH	H
A1	11	10					A1			10	11			A1					10	11
A2				10	11		A2		10	10	10			A2	11	10				
A3					10	11	A3						12	A3		10	10	10		
A4						12	A4				10	11		A4			10	10	10	
A5				11	10		A5				10	11		A5					11	10
A6				10	11		A6					12		A6					10	11
A7			10	10	10		A7					12		A7	10	10	10			
A8		10	10	10			A8			10	10	10		A8					12	
option	(C4)						option	(C5)						option	(C6)					
	VL	L	FL	M	FH	H		VL	L	FL	M	FH	H		VL	L	FL	M	FH	H
A1	12						A1	12						A1		11		10		
A2				11	10		A2				10		11	A2	12					
A3						12	A3				10		11	A3	12					
A4						12	A4					10	11	A4	11	10				
A5	10	11					A5	11		10				A5				10		11
A6	10	11					A6	10		10	10			A6					11	10
A7					11	10	A7		10			11		A7	11		10			
A8	11	10					A8	10	10		10			A8				10	10	10
option	(C7)						option	(C8)						option	(C9)					
	VL	L	FL	M	FH	H		VL	L	FL	M	FH	H		VL	L	FL	M	FH	H
A1	11		10				A1	10	11					A1			10	11		
A2			10		11		A2	12						A2				10	10	10
A3				10	11		A3	12						A3						12
A4						12	A4	12						A4					12	
A5		12					A5		10		11			A5	10	10		10		
A6	12						A6					12		A6		10	10		10	
A7		10	10	10			A7				10	11		A7					10	11
A8	11		10				A8					10	11	A8				11	10	

option	(C10)					
	VL	L	FL	M	FH	H
A1				11		10
A2					11	10
A3						12
A4						12
A5					12	
A6		10		11		
A7					11	10
A8			11	10		

In the figure above, where the number 11 is written, for example, it means that 11 experts had a common opinion. For example, in the first criterion, the experts stated the number 12 in column H for the fourth option. This means that 12 experts stated the importance of the first criterion in the fourth option as "high".

In the next step, the initial matrix is descaled. In other words, this matrix is linearly normalized. The normalized values are shown in Table 8.

Table 8. Quantitative matrix in Shannon entropy method

Quantitative Matrix	+	+	+	+	-	+	+	+	+	+
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**
A1	2.333	6	9	2	2	4	3	2.666	5.666	7
A2	7.333	8	9	2.666	4.333	8.333	2	8	5.333	5
A3	6.666	7	8	2.666	3	8	3	5	3.666	8
A4	4.666	6	8	2.333	3.666	7.666	3	8.666	6.66	5.333
A5	7.333	5	2	6.666	8	2	7	2	7.666	8.333
A6	6.333	8	3	8.333	6.333	3	4.666	7.333	8.666	8.333
A7	9	7	6	9	8.666	2.333	9	2	8	9
A8	8.666	9	5	9	8	2	7.333	2	9	9

Table 9. Linear Normalization of the Initial Matrix Values

Non-dimensional Linear	+	+	+	+	-	+	+	+	+	+
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**
A1	0.0446	0.1006	0.1722	0.0469	0.0455	0.1071	0.0769	0.0708	0.1037	0.1167
A2	0.1401	0.1420	0.1722	0.0625	0.0985	0.2232	0.0513	0.2124	0.0976	0.0833
A3	0.1274	0.1302	0.1656	0.0625	0.0682	0.2143	0.0769	0.1327	0.0671	0.1333
A4	0.0892	0.1124	0.1598	0.0547	0.0833	0.2054	0.0769	0.2301	0.1220	0.0889
A5	0.1401	0.0828	0.0464	0.1563	0.1818	0.0536	0.1795	0.0531	0.1402	0.1389
A6	0.1210	0.1420	0.0662	0.1953	0.1439	0.0804	0.1197	0.1947	0.1585	0.1389
A7	0.1720	0.1302	0.1258	0.2109	0.1970	0.0625	0.2308	0.0531	0.1463	0.1500
A8	0.1656	0.1598	0.0927	0.2109	0.1818	0.0536	0.1880	0.0531	0.1646	0.1500

Given that the number of criteria used is 8, the value of the K coefficient is calculated as follows:

$$K = \frac{1}{\ln 8} = 0.4809 \quad (43)$$

Considering the value of this coefficient, the entropy related to each criterion, the degree of deviation, and the normalized weight of each criterion are determined in Table 9.

Table 10. Entropy values for each criterion, degree of deviation, and normalized weight of each criterion

Criterion		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Entropy of each index	Ej	0.9731	0.9913	0.9615	0.9207	0.9512	0.9227	0.9422	0.9180	0.9837	0.9902
Deviation degree	dj	0.0269	0.0087	0.0385	0.0793	0.0488	0.0773	0.0578	0.0820	0.0163	0.0098
Normalized weight	Wj	0.0603	0.0196	0.0864	0.1780	0.1096	0.1735	0.1298	0.1841	0.0366	0.0220

Finally, based on the relative weights determined for each criterion by experts, the final weight of each criterion was calculated as shown in Table 10:

Table 11. Calculating the final weight of the criteria

Criterion	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Relative Weight	0.18	0.15	0.05	0.06	0.1	0.1	0.17	0.07	0.04	0.08
$\lambda_j W_j$	0.0109	0.0029	0.0043	0.0107	0.011	0.0174	0.0221	0.0129	0.0015	0.0018
W'j	0.1139	0.0309	0.0453	0.1121	0.115	0.1821	0.2315	0.1353	0.0153	0.0185

Based on the results obtained, the seventh criterion, "Average Wind Speed," has the highest weight, while the ninth criterion, "Access to the Site," has the lowest weight.

4.2. Ranking of Reconstruction Options

As mentioned, in this study, the AHP method was used to select the best reconstruction option for the Zarshuran Gold Mine. Initially, to create an initial matrix for the AHP method, the experts' opinions were integrated and prepared as a fuzzy matrix. Table 11 shows the fuzzy matrix after integrating the experts' opinions.

The next step was to unscale the matrix obtained from merging the experts' opinions. The normalized fuzzy matrix is shown in Table 12.

Table 12. Fuzzy matrix resulting from merging expert opinions

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
A1	(6.2,3.4,1.6)	(9.7, 7.9,4.11)	(2.13,9.14, 7.16)	(1,2,3)	(1,2,3)	(6,25.7,5.9)	(25.4,6,75.7)	(7.2,4.4,2.6)	(9.7, 7.9,4.11)	(25.11,13,75.14)
A2	(6.10,3.12,1.14)	(2.9, 7.11,2.14)	(6.2,3.4,2.5)	(4.10,2.12,9.13)	(5.11,25.13,15)	(1,2,3)	(75.9,5.11,25.13)	(1,2,3)	(7.16,2.19, 7.21)	(1.13,8.14,6.16)
A3	(2.13,9.14,7.16)	(8,9,10)	(2.9, 7.11,2.14)	(8,9,10)	(5.11,25.13,15)	(1,2,3)	(6.10,3.12,1.14)	(1,2,3)	(8,9,10)	(8,9,10)
A4	(8,9,10)	(6.10,3.12,1.14)	(3.13,8.15,3.18)	(8,9,10)	(2.13,9.14, 7.16)	(6.2,3.4,1.6)	(8,9,10)	(1,2,3)	(7,8,9)	(8,9,10)
A5	(4.10,2.12,9.13)	(6.10,3.12,1.14)	(1.13,8.14,6.16)	(7.2,4.4,2.6)	(25.4,6,75.7)	(5.11,25.13,15)	(2,3,4)	(25.6,8,75.9)	(7.6,2.9, 7.11)	(7,8,9)
A6	(6.10,3.12,1.14)	(7,8,9)	(2.13,9.14, 7.16)	(7.2,4.4,2.6)	(3.8,8.10,3.13)	(1.13,8.14,6.16)	(1,2,3)	(7,8,9)	(8.10,3.13,8.15)	(25.6,8,75.9)
A7	(3.13,8.15,3.18)	(7,8,9)	(8.5,3.8,8.10)	(1.13,8.14,6.16)	(1.8,8.9,6.11)	(25.4,6,75.7)	(2.9,7.11,2.14)	(6.10,3.12,1.14)	(2.13,9.14, 7.16)	(1.13,8.14,6.16)
A8	(2.13,9.14, 7.16)	(8,9,10)	(2.9, 7.11,2.14)	(8,9,10)	(5.11,25.13,15)	(1,2,3)	(6.10,3.12,1.14)	(1,2,3)	(8,9,10)	(8,9,10)

Table 13. Fuzzy Normalized Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
A1	(14, 24, 3)	(43, 53, 62)	(72, 81, 91)	(06, 12, 18)	(06, 12, 18)	(28, 36, 44)	(3, 42, 55)	(16, 27, 37)	(37, 45, 53)	(68, 78, 89)
A2	(58, 67, 7)	(5, 64, 77)	(14, 24, 28)	(63, 73, 84)	(69, 8, 9)	(05, 09, 14)	(69, 81, 94)	(06, 12, 18)	(77, 88, 1)	(79, 89, 1)
A3	(72, 81, 91)	(44, 49, 55)	(5, 64, 77)	(48, 54, 6)	(69, 8, 9)	(05, 09, 14)	(75, 87, 99)	(06, 12, 18)	(37, 42, 46)	(48, 54, 6)
A4	(4, 49, 5)	(58, 67, 77)	(73, 86, 1)	(48, 54, 6)	(79, 9, 1)	(12, 2, 28)	(56, 64, 71)	(06, 12, 18)	(32, 37, 42)	(48, 54, 6)
A5	(57, 6, 76)	(58, 67, 77)	(71, 81, 9)	(16, 27, 37)	(26, 36, 47)	(53, 61, 69)	(14, 21, 28)	(38, 48, 59)	(31, 42, 54)	(42, 48, 54)
A6	(58, 67, 7)	(38, 44, 49)	(72, 81, 91)	(16, 27, 37)	(5, 65, 8)	(6, 68, 77)	(07, 14, 21)	(42, 48, 54)	(5, 62, 73)	(38, 48, 59)
A7	(73, 86, 1)	(38, 44, 49)	(32, 45, 59)	(79, 89, 1)	(49, 59, 7)	(2, 28, 36)	(65, 82, 1)	(64, 74, 85)	(61, 69, 77)	(79, 89, 1)
A8	(5, 64, 7)	(73, 86, 1)	(38, 44, 49)	(16, 26, 37)	(4, 55, 7)	(77, 88, 1)	(3, 42, 55)	(79, 9, 1)	(48, 56, 64)	(5, 61, 72)

In the final stage, after defuzzification of the normalized matrix, the rank of each option was calculated. According to the results obtained, which are included in Table 16, the reconstruction options were prioritized as follows:

A1< A5 < A6 < A3 < A4 < A2 < A8 < A7

According to the results, the seventh option (using a solar power plant) was selected as the best option. Considering the climatic conditions of the relevant region, this option is approved. It should be noted that based on the information received from the meteorological site, the study area has 312 sunny days per year.

Table 14. Results of ranking mine rehabilitation options

Defuzzification						
Ranking	**α (Right)**	**α (Left)**	**Ranking (Center of Area)**	**Center of Area (BNP)**	**Total**	**Option**
8	0.4104	0.488	0.3328	0.4096	0.7059	A1
3	0.5877	0.6772	0.4983	0.5861	0.8853	A2
5	0.5351	0.6216	0.4485	0.5318	0.8082	A3
4	0.5386	0.6185	0.4587	0.5335	0.8166	A4
7	0.5047	0.5799	0.4295	0.4978	0.674	A5
6	0.5659	0.6509	0.4809	0.5244	0.747	A6
1	0.6734	0.7795	0.5672	0.6663	0.9409	A7
2	0.6173	0.7137	0.5209	0.612	0.8542	A8

5. Conclusions

Over the past two decades, the focus of mining stakeholders on preserving environmental quality has gradually increased, influencing rehabilitation, design, and mining activities. Mining operations, if not carried out with precision, not only harm the environment but also pose challenges to post-extraction land preparation. Conversely, rehabilitation operations that disregard environmental considerations will lack technical and economic justification. Mining worldwide occurs under diverse climatic conditions, including extreme temperatures and varying humidity levels. These factors, along with environmental and ecological conditions, topography, and soil status, can act as limiting factors in selecting a rehabilitation method. Today, renewable energy sources like solar, water, wind, and geothermal are gaining significant attention as limitless energy sources, offering advantages over fossil fuels in terms of environmental impact, sustainability, and safety. Renewable energy can also provide lower energy prices and create jobs. This study, therefore, emphasizes the use of renewable energy after mine closure as a new rehabilitation strategy aligned with sustainable development concerns.

One crucial consideration in selecting rehabilitation strategies is the possibility of combining some options. For instance, the "wind farm construction" and "agricultural land use" options can be implemented simultaneously, as wind turbines do not occupy much physical space, allowing crops to be grown in the surrounding land. In this study, such combinations were not explicitly analyzed, but future research should explore the feasibility of integrating multiple strategies to maximize economic and environmental benefits.

In this research, eight viable rehabilitation options for the Zarshuran Gold Mine were identified by a team of experts, along with ten criteria affecting these options. Using the fuzzy AHP method, it was determined that constructing a solar power plant is the most optimal rehabilitation option for the Zarshuran Gold Mine. This choice aligns with the region's potential, particularly the high number of sunny days per year, and was supported by the expert group. The study demonstrates the effectiveness of FAHP as a decision-making tool in a complex, multi-criteria context. Future research can focus on developing dynamic reclamation models that incorporate changing conditions and explore integrated approaches while also prioritizing community engagement and detailed environmental impact assessments. Standardized metrics for evaluating reclamation success across diverse contexts are also needed to enable objective comparisons and identify best practices.

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انتخاب روش مناسب بازسازی در معادن روباز با استفاده از روش‌های تصمیم‌گیری

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کلمات کلیدی

بازسازی

معادن روباز

تصمیم‌گیری

معدن طلای زرشدوران

فرآیند تحلیل سلسله مراتبی فازی

چکیده

بازسازی معادن روباز برای مدیریت اثرات زیست‌محیطی و دستیابی به توسعه پایدار پس از اتمام عملیات معدنی ضروری است. هدف این مطالعه یافتن بهترین روش برای بازسازی معدن طلای زرشدوران از طریق رتبه‌بندی هشت روش مختلف بازسازی با استفاده از فرآیند تحلیل سلسله‌مراتبی فازی (FAHP) است. این گزینه‌ها شامل بازگرداندن معدن به حالت اولیه، کاشت درخت، ساخت مزرعه بادی، ایجاد منطقه تفریحی، راه‌اندازی چراگاه‌ها، کشاورزی، ساخت نیروگاه خورشیدی، و ایجاد جاذبه‌های گردشگری هستند. پانلی متشکل از دوازده کارشناس این گزینه‌ها را بر اساس ده معیار کلیدی ارزیابی کردند: شدت دمای هوا، تعداد روزهای آفتابی، شرایط خاک، فاصله از مناطق مسکونی، ناهمواری‌های توپوگرافی، تراکم پوشش گیاهی، سرعت متوسط باد، گونه‌های حیوانی محلی، دسترسی به سایت، و اندازه و شکل منطقه معدنی. نتایج نشان می‌دهند که ساخت نیروگاه خورشیدی به عنوان مناسب‌ترین گزینه بازسازی برای معدن طلای زرشدوران شناخته شده است، با توجه به شرایط اقلیمی منطقه (به‌ویژه تعداد بالای روزهای آفتابی در سال) و پتانسیل آن برای تولید انرژی پاک و ایجاد درآمد. این مطالعه بر اهمیت در نظر گرفتن معیارهای زیست‌محیطی، اجتماعی و فنی در فرآیند تصمیم‌گیری برای بازسازی معادن تأکید دارد و چارچوبی برای انتخاب روش‌های پایدار بازسازی در زمینه‌های معدنی مشابه ارائه می‌دهد.

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