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AN INTEGRATED SUSTAINABLE FRAMEWORK FOR ECOLOGICAL RISK ASSESSMENT IN MINING PROJECTS

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Highlights:

- this paper integrates the fuzzy analytic hierarchy process with the COPRAS technique to evaluate the ecological risks in an open pit mine;
- the proposed model uses the Leopold matrix to identify the most critical risks;
- a case study illustrates the risk assessment process in a step-by-step procedure;
- authorities can utilize the outputs to select the best preventive measures.

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Abstract. Mining is a dangerous activity associated with adverse environmental, social, and economic effects. The underlying reason for environmental impact assessment is to evaluate and eliminate mining operations' physical, social, economic, and biological impact on the existing environment. However, different models have been developed to assess the environmental impacts. The Leopold matrix is a systematic approach that helps authorities evaluate mining projects based on environmental impacts. However, the Leopold matrix is criticized for its inability to consider the inherent uncertainty imposed by the problem under consideration. On the other hand, fuzzy logic is a robust mathematical tool for facing such situations. Likewise, Multi-Criteria Decision-Making (MCDM) techniques are among the most appropriate methods for formulating a complex and sophisticated problem. Therefore, the paper proposed a hybrid evaluation model using the COPRAS technique and the Analytical Hierarchy Process (AHP) method under a fuzzy environment where the uncertainties are formulated with linguistic variables. This article proposes to use the Leopold matrix to extract the factors and actions. Then, the fuzzy AHP helped determine the criteria and sub-criteria weights. Finally, fuzzy COPRAS computes the utility degree of options. A case study presents the potential use of the proposed model. The results showed that transportation is located in the first rank with the comparative preference and the utility degree of 0.832 and 100, respectively.

Keywords: fuzzy AHP, COPRAS, ecological risk assessment, open pit mine.

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1. Introduction

Mining is known as a process of the extraction of natural resources. Mining development is a substantial parameter for economic growth. Mining product revenue and service industries contribute more than 45% to global GDP[1]. Mining development can be a catalyst for social growth in many countries[2]. However, mining activities are known as hazardous operations that cause damage to property, loss, injury to human lives, interruption in production, etc. However, mining generates considerable waste, resulting in detrimental effects for decades. Therefore, mining is among the greatest threats to the planet's environment, as it changes river regimes and water tables, destroys natural habitats, and causes other severe natural effects (Macklin et al., 2023). The mining industry contributes between 4 and 7% of global greenhouse gas emissions[3].

Since a large part of the earth is permanently removed from future beneficial use, mining operations should be fulfilled without damaging the environment (Agboola

1 http://www.miningweekly.com
2 https://mining2030.org/
3 https://theintelligentminer.com/2022/10/26/the-role-of-mining-in-mitigating-the-effects-of-climate-change/

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et al., 2020; Xu et al., 2021; Zhang et al., 2021; Ghosh et al., 2023). Nowadays, an overarching goal is to find ways in which the mining sector can eliminate or diminish the hazards associated with mining activities. In many countries, before starting a mining project, an Environmental Impact Assessment (EIA) is required (Environmental Law Alliance Worldwide [ELAW], 2010; Ayiwouo et al., 2023). Therefore, the EIA process is a critical part of mine development to diminish the potential effects of a mining project (Worlanyo & Jiangfeng, 2021). This process helps authorities consider social, economic, and technical components to minimize ecological degradation (International Atomic Energy Agency [IAEA], 2005; Pouresmaieli et al., 2023). Since ecological preventive measures cost less than 3% of the capital, the EIA is necessary for a new or development project to prevent spending much money on environmental disturbances[4]. However, the traditional approaches are unable to comprehensively evaluate a decision process because of complexity and uncertainty involved in the decision process. These approaches often only take into account the qualitative data and ignore the qualitative information.

The EIA, integrating environmental factors with decision-making and project planning, is a systematic procedure for predicting the ecological effects of an activity before planning and undertaking. This tool minimizes the impact of an intentional action on the environment (Chen et al., 2023; Paustenbach et al., 2024). The process aims to analyze the ecological consequences of accomplishing a progress scheme before making unreliable decisions (IAEA, 2005). The EIA procedure is a salient process (1) to recognize the negative and positive effects on the ecology in the long and short time, (2) to decrease the adverse effects of an action to reduce environmental degradation, and (3) to provide a checking procedure to monitor how a project is implemented and measure the successful rate of the protective activities (Rikhtegar et al., 2014).

Since many factors can meaningfully impact the environmental problem, the EIA process is a bothersome and complex activity. Therefore, the value of employing Multi-Criteria Decision-Making (MCDM) is to take into account both tangible and intangible components (Borujeni & Gitinavard, 2017; Gitinavard, 2019; Gitinavard et al., 2020; Solgi et al., 2021).

The COPRAS (COmplex PRoportional ASsessment) technique, introduced by Zavadskas et al. (1994), is a branch of the MCDM methods. Several researchers have demonstrated the effectiveness and capability of the COPRAS technique (Fouladgar et al., 2012a, b; Yazdani-Chamzini et al., 2013; Rabbani et al., 2014; Mulliner et al., 2016; Valipour et al., 2017; Feng et al., 2017; Zarbakhshnia et al., 2018; Pancholi & Bhatt, 2018). The main reasons for the popularity of the COPRAS technique comprise (i) simultaneous considerations of the ratio to the ideal solutions (Fouladgar et al., 2012a, b), (ii) simple and logical computations (Yazdani-Chamzini et al., 2013), (iii) a lower calculation time in comparison to other decision techniques (Mulliner et al., 2016), and (iv) less biased and more efficient than those yielded by TOPSIS (The Technique for Order of Preference by Similarity to Ideal Solution).

However, the COPRAS technique cannot handle the inherent vagueness imposed in modeling a decision problem; without considering the vagueness, the results will be inaccurate and maybe a root reason for the unreliable analysis. On the other hand, fuzzy logic is a powerful technique for formulating the uncertainty resulting from lack or less of information (Deveci et al., 2023). Therefore, the fuzzy COPRAS technique is introduced to integrate the benefits of both the COPRAS method and fuzzy logic into a robust approach for solving a sophisticated and complex decision problem.

On the other hand, fuzzy AHP (FAHP) is a powerful mathematical tool that combines the advantages of analytical hierarchy structure with fuzzy logic theory (Rufuss et al., 2018; Iphar & Cukurluoz, 2018; Li et al., 2020). This technique uses two-by-two pairwise comparisons to construct the decision matrix. The FAHP approach uses a hierarchical structure to make an organized connection among the elements. This method, an intuitive and moderately simple approach, can consider both intangible and tangible components.

Therefore, a sustainable risk index based on environmental impacts must be defined to investigate the risk level quantitatively and qualitatively. This method proposes a predominant scientific approach and critically evaluates numerical data and qualitative information to identify and feasibly quantify the hazards connected to a potential threat. The research introduces a combined model based on the two MCDM methods for environmental risk assessment under the Leopold matrix parameters regarding linguistic values. The main aim is to propose a powerful and robust model for evaluating ecological risk assessment under a sustainable framework in mining projects. The proposed model can consider the technical, operational, and ecological factors and social parameters. The model can help authorities to implement the best preventive measures in facing adverse conditions. This study investigates a mining project for responding to the following questions:

Which parameters can significantly impact ecological risk assessment in mining projects?

- How can the extracted parameters from the previous step influence ecological risk assessment?
- How is the relative importance among the criteria and sub-criteria?
- How is the relative preference among the different actions?
- How is the priority of ecological risks in mining projects?

The breakthrough of the study is to provide a systematic framework for identifying and evaluating ecological degradations imposed by mining projects to make a proper decision in facing such damages. This can significantly

[4] https://ora.ox.ac.uk/objects/uuid:4aebccbd-ae2d-4905-8e26-98db84e51272/files/srv042w25c

reduce the harmful effect of mining activities. It should be noted that the environmental costs of preventing, reducing, or compensating for adverse environmental impacts of mining activities of the open-pit option are equal to 0.02927 $ / ton Ore (and Waste) (Badakhshan et al., 2023).

2. Literature review

Since the environmental impacts generated by mining operations cannot be completely obliterated, many techniques have been introduced to evaluate an ecological impact problem, including checklists, matrices, graphs, and superimposed maps. Checklists provide a default list of possible impacts. Matrices, known as a two-dimensional checklist, use the analysis of cause-effect relationships to assess the environmental impacts. Graphs (networks) describe the network of causal effects. The superimposed map is a simple technique for displaying the impact areas.

Standards Australia and Standards New Zealand (2004) developed a qualitative risk assessment matrix to assess the environmental risks based on environmental effects and probability for mining projects. IAEA (2005) employed a weighted checklist to evaluate the ecological risk level in mining projects. Leopold et al. (1971) introduced an EIA matrix based on magnitude and importance for the impact assessment of a mining project. The environmental impact of a mining project using Interferometric SAR is assessed by Woldai and Taranik (2008). Ellis and Connolly (1996) developed a guideline based on the checklist for evaluating the environmental impacts.

Valizadeh and Shekari (2015) employed the Leopold matrix for the EIA of solid waste. Rigina (2002) used remote sensing methods for integrated EIA to evaluate the industrial pollution from concentration and mining activities. Collins et al. (2013) conducted the EIA of mining activities at seafloor massive sulfide deposits. ELAW (2010) proposed a guidebook based on the EIA for evaluating mining projects. This guidebook can help authorities investigate the techniques that can significantly diminish the potential hazards of extraction activities. Ataei et al. (2016) used the matrix method to introduce a quantifiable framework for the EIA. They determined the environmental parameters and corresponding influencing indicators. Folchi (2003) introduced a new method to measure the ecological effect of extraction projects. Dahlmanns et al. (2024) used the AHP method and the Leopold matrix to assess the intensity of the impact of the Křoví mining facility on the environment. Ayiwouo et al. (2023) used the Leopold matrix and the Fecteau grid to identify the environmental impacts and to determine their absolute importance. Amiri et al. (2024) evaluated the environmental impact assessment of Mine Utilization using the Iranian Leopold Matrix. Tianliang et al. (2023) evaluated the environmental impact assessment of the Goliran Coal Mine in northern Iran using the Leopold matrix and the Rapid Impact Assessment.

Venkataraman et al. (1997) used cluster analysis, factor analysis, and the Leopold matrix method to investigate the effects of opencast mines with the help of limited ground-based information and remote sensing data. Phillips (2012a) developed a model grounded on the quantitative EIA to assess abandoned limestone quarries. Phillips (2012b) employed a sustainable model in the EIA of an extraction development plan. Berg (2017) investigated the process of the EIA in mines and proposed an environmental management program for facing ecological issues. Monjezi et al. (2009) evaluated the environmental effect of mining activities using the Folchi method.

Jantunen et al. (2015) presented an EIA guidebook to create information on the effects of a mining development plan, consider the environmental problems in the evaluation process, and provide an opportunity for decision-makers to participate in and affect these processes. Johansen and Asmund (1999) investigated the ecological effects of an extraction development plan. Namin et al. (2011) presented an approach grounded in the Folchi algorithm to select the mining method using the EIA process.

An EIA model grounded on decision-making techniques is proposed by Rikhtegar et al. (2014) to investigate the environmental risks associated with mining operations. They utilized the analytic network process method to calculate the importance weights and the fuzzy simple additive weight to calculate the ratings of the options. Cleary and Thornton (1994) conducted a comprehensive investigation into the environmental effects of gold mines. Rees and Rigina (2003) investigated the impact of extraction operations on adverse ecological phenomena.

On the other hand, mining operations have detrimental environmental impacts on land, water, air, flora, and fauna. Mining activities significantly influence air quality by releasing unrefined particles to the surface. These unrefined particles are generally composed of toxic materials[5]. Such materials adversely affect the health of humans and animals. Likewise, mining can lead to the physical destruction of land by changing the surrounding topography. Usually, the topography structure of the area cannot be modified after mining. Such destruction can contribute to the deterioration of the flora and fauna in the area[6].

On the other hand, ground vibration and subsidence influenced by mining activities can damage buildings and infrastructure. Mining operations can also affect water pollution by draining acidic mines and contaminating the metal. The different sources impact water pollution, comprising waste-disposal areas, tailing ponds, and processing plants. Mining may lead to sizeable massive habitat losses, damaging animals, vegetation, and microorganisms.

3. The integrated model

3.1. Leopold matrix

A two-dimensional matrix with a hundred specified actions and eighty-eight environmental components is introduced by Leopold et al. (1971). This method represents one of

[5] https://www.worldatlas.com/
[6] https://www.worldatlas.com/

the first attempts to relate development actions and components of the environment using the numerical weighting of probable impacts (Salehi et al., 2023; Jahanishakib & Salary, 2023; Ayiwouo et al., 2023; Amiri et al., 2024; Rahimi & Khoshfetrat, 2024). This matrix takes into account each action and the corresponding potential for influencing each environmental item (Hosseini & Norouzi, 2023; Leite et al., 2024). For the magnitude of the interaction (scale or extensiveness), the matrix allocates a value ranging from 1 to 10, where 1 indicates the minimum magnitude and 10 represents the maximum magnitude. The values are assigned based on a comprehensive analysis of the existing data and information. The matrix also proposes a scale of 1 to 10 for the importance, where 1 addresses the slightest interaction, and 10 indicates the most interaction. The values for importance are determined based on the subjective judgment of decision-makers. The matrix approach, a gross screening technique to identify the impacts, is reasonably flexible[7]. Figure 1 shows the components of the Leopold matrix.

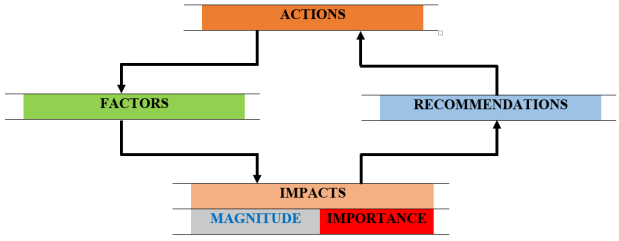


Figure 1. Components of the Leopold matrix

3.2. Fuzzy set theory

Zadeh (1965) introduced the fuzzy set theory to handle the inherent imprecision connected with the decision process. This theory helps authorities deal with the ambiguity imposed by the linguistic evaluation of the information. A fuzzy set uses membership functions, with the value of the closed interval [0,1], to define a fuzzy value (Özdemir et al., 2025). Where 0 indicates non-membership, and 1 represents full membership of an element. At the same time, the other values address partial membership of an element. A membership function with a higher value indicates greater belongingness of a component to the universal set (Erdem et al., 2025). Assuming that $\tilde{A}=(a,b,c)$ is a triangular fuzzy number (TFN), the membership function $\mu_A(x)$ is mathematically as follows:

$$\mu_A(x)=\begin{cases}(x-a)/(b-c) & a\le x\le b,\\ (x-c)/(b-c) & b\le x\le c,\\ 0, & \text{otherwise},\end{cases} \quad (1)$$

where a indicates the lower value, b expresses the middle value, and c represents the upper value, and $a\le b\le c$.

A TFN can be used in situations where some attribute values need to be expressed objectively to convey the decision-making information. This not only maintains the variable's value in an interval, but also displays the likelihood of different values in the considered interval (Arora & Naithani, 2023).

Under some assumptions about the underlying density probability function, the fuzzy set established by a TFN leads to entropy equalization. Similarly, the TFN with 1/2 the overlap level produces the zero value of the reconstruction error (Pedrycz, 1994).

3.3. Fuzzy AHP

Saaty (1980) introduced the Analytical Hierarchy Process (AHP) to solve a complex issue by decomposing it into several simple problems in a hierarchical structure. This method computes the relative weight of elements by the pairwise comparison process. However, the AHP technique, generally employed in a decision problem with exact information, is unable to formulate the uncertainty connected to the modeling process. Therefore, a hybrid of fuzzy logic with the AHP technique (FAHP) can solve the problem of uncertainty and ambiguity. Several FAHP techniques have been developed to solve an organized decision issue (Deng, 1999). This paper adopts Chang's extent analysis method (Chang, 1996) because it is less computational expense, less time-consuming, and relatively more straightforward.

The procedure of Chang's extent analysis method is as follows: Let U = $\{u_1, u_2, \ldots, u_m\}$ be a goal set and X = $\{x_1, x_2, \ldots, x_n\}$ be an object set. Based on the basic concepts of the method, each object is considered, and the extent of analysis for each goal, g_i, is fulfilled. Therefore, m extent analysis values for each object are yielded as follows:

$$M_{gi}^1, M_{gi}^2, \ldots, M_{gi}^m, \; i=1,2,\ldots,n, \quad (2)$$

where all the $M_{gi}^j (j=1,2,\ldots,m)$ indicate TFNs.

Chang's extent analysis is step-by-step defined as follows:

Step 1. – Concerning the ith object, the value of fuzzy synthetic extent is described as:

$$S_i=\sum_{j=1}^{m} M_{gi}^j \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^j\right]^{-1}. \quad (3)$$

The following equation is performed to obtain:

$$\sum_{j=i}^{m} M_{gi}^j : \sum_{j=1}^{m} M_{gi}^j = \left(\sum_{j=1}^{m} l_i, \sum_{j=1}^{m} m_i, \sum_{j=1}^{m} u_i\right). \quad (4)$$

And to obtain $\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^j\right]^{-1}$, perform the fuzzy addition operation of $M_{gi}^j (j=1,2,\ldots,m)$ values:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^j = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i\right). \quad (5)$$

Next, calculate the inverse vector by Eq. (5):

$$\left[\sum_{n=1}^{n}\sum_{j=1}^{m} M_{gi}^j\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right). \quad (6)$$

[7] https://www.adb.org/sites/default/files/publication/29779/eia-developing-countries-asia.pdf

Step 2. – The rate of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ can be described as:

$$V(M_2 \geq M_1) = \sup_{y \geq x}\left[\min(\mu_{M1}(x), \mu_{M2}(y))\right] \quad (7)$$

The following equation equally indicates this:

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M2}(d) = \begin{cases} 1, & \text{if } m_2 \geq m_1 \\ 0, & \text{if } l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & \text{otherwise,} \end{cases} \quad (8)$$

where d indicates the ordinate of the highest intersection point D between μ_{M1} and μ_{M2}.

The values of $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$ are calculated to compare M_1 and M_2.

Step 3. – The possibility rate for a convex fuzzy number is calculated.

Step 4. – A normalization process computes the normalized weight vectors.

3.4. Fuzzy COPRAS

The COPRAS method is widely used to solve an MCDM problem Zavadskas et al. (1994). This technique obtains a solution with the ratio to the best solution. The method assigns the best alternative by combining the values allocated to the feasible options with those of the evaluation criteria in the utility function. In the basic form of the COPRAS technique, the ratings of alternatives were determined by numerical data. However, there is no perfect knowledge of options in many situations because of a lack of information. Therefore, assigning a precise rate for the alternatives under consideration is impossible. Consequently, fuzzy COPRAS is developed to assign preference ratings to other options using verbal terms and fuzzy numbers (Yazdani et al., 2011). The fuzzy COPRAS is illustrated as follows:

Step 1. Determining the linguistic ratings for alternatives. Table 1 shows verbal values and corresponding fuzzy numbers for alternatives.

Table 1. Linguistic rating for alternatives

Linguistic term	Fuzzy number
Very high (VH)	(7, 9, 10)
High (H)	(5, 7, 9)
Moderate (M)	(3, 5, 7)
Low (L)	(1, 3, 5)
Very low (VL)	(0, 1, 3)

Step 2. Constructing the decision matrix.

The decision matrix with m rows and n columns can be obtained where the count of criteria is n, and the number of alternatives is m:

$$\tilde{D} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & & \tilde{x}_{mn} \end{bmatrix} \end{array}. \quad (9)$$

Step 3. Defuzzifing the decision matrix. Different algorithms are developed for the defuzzification process. The center of the area (COA) method is adopted to deffuzzify the fuzzy decision matrix. This method is a simple and practical algorithm without a preference process (Wu et al., 2009). The BNP rate for $\tilde{R}_i = (L\tilde{R}_i, M\tilde{R}_i, U\tilde{R}_i)$ is as follows:

$$BNP_i = \left[\left(U\tilde{R}_i - L\tilde{R}_i\right) + \left(M\tilde{R}_i - L\tilde{R}_i\right)\right] / 3 + L\tilde{R}_i. \quad (10)$$

Step 4. Normalizing the defuzzied matrix $\bar{X}$ he normalization process developed by Zavadskas (1987) is as follows:

$$\bar{x}_{ij} = \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}}; \; i = \overline{1,n} \text{ and } j = \overline{1,m}. \quad (11)$$

Therefore, the normalized matrix is obtained as:

$$\bar{X} = \begin{bmatrix} \bar{x}_{11} & \bar{x}_{12} & \cdots & \bar{x}_{1m} \\ \bar{x}_{21} & \bar{x}_{22} & \cdots & \bar{x}_{2m} \\ \vdots & \vdots & \cdots & \vdots \\ \bar{x}_{n1} & \bar{x}_{n2} & \cdots & \bar{x}_{nm} \end{bmatrix}. \quad (12)$$

Step 5. Calculating the weighted normalized matrix $\bar{X}$. The values $\hat{x}_{ij}$ are obtained as follows:

$$\hat{x}_{ij} = \bar{x}_{ij} \cdot q_j; \; i = \overline{1,n} \text{ and } j = \overline{1,m}, \quad (13)$$

where denotes the weight of the attribute.

The weighted normalized matrix can be yielded as follows:

$$\hat{X} = \begin{bmatrix} \hat{x}_{11} & \hat{x}_{12} & \cdots & \hat{x}_{1m} \\ \hat{x}_{21} & \hat{x}_{22} & \cdots & \hat{x}_{2m} \\ \vdots & \vdots & \cdots & \vdots \\ \hat{x}_{n1} & \hat{x}_{n2} & \cdots & \hat{x}_{nm} \end{bmatrix}; \; i = \overline{1,n} \text{ and } j = \overline{1,m}. \quad (14)$$

Step 6. Summing the values of the benefit criteria:

$$P_i = \sum_{j=1}^{k} \hat{x}_{ij}, \quad (15)$$

where k indicates the number of benefit criteria.

Step 7. Summing the values of R_j the cost criteria:

$$R_i = \sum_{j=k+1}^{m} \hat{x}_{ij}, \quad (16)$$

where indicates the number of cost criteria.

Step 8. Obtaining the minimum value of R_i:

$$R \min_i \overline{1,n}_{\min}. \quad (17)$$

Step 9. Calculating the comparative preference of each option:

$$Q_i = P_i + \frac{R\sum_{i=1}^{n} R_{imin}}{R_i \sum_{i=1}^{n\Sigma} \frac{R_{min}}{R_i}}. \quad (18)$$

This equation can be rewritten as:

$$Q_i = P_i + \frac{\sum_{i=1}^{n} R_i}{R_i \sum_{i=1}^{n} \cdot \frac{1}{R_i}}. \quad (19)$$

Step 10. Determining the optimum criterion K:

$$K = \max_i Q_i; \ \ i = \overline{1,n}. \quad (20)$$

Step 11. Determining the priority of the feasible alternatives. The greater the weight, the higher the priority (rank). The satisfaction degree in the case of Q_{max} is the highest.

Step 12. Calculating the utility degree for each option:

$$N_i = \frac{Q_i}{Q_{max}}. \quad (21)$$

3.5. The proposed model

The model developed for environmental risk assessment in open pit mines comprises the following stages: (i) identify factors and actions based on the Leopold matrix, (ii) assign the importance weights of the components by using the FAHP method based on the scale given in Table 2, (iii) investigate the actions concerning the factors by using the fuzzy COPRAS technique, and (iv) determine the risk level for the actions based on the outputs.

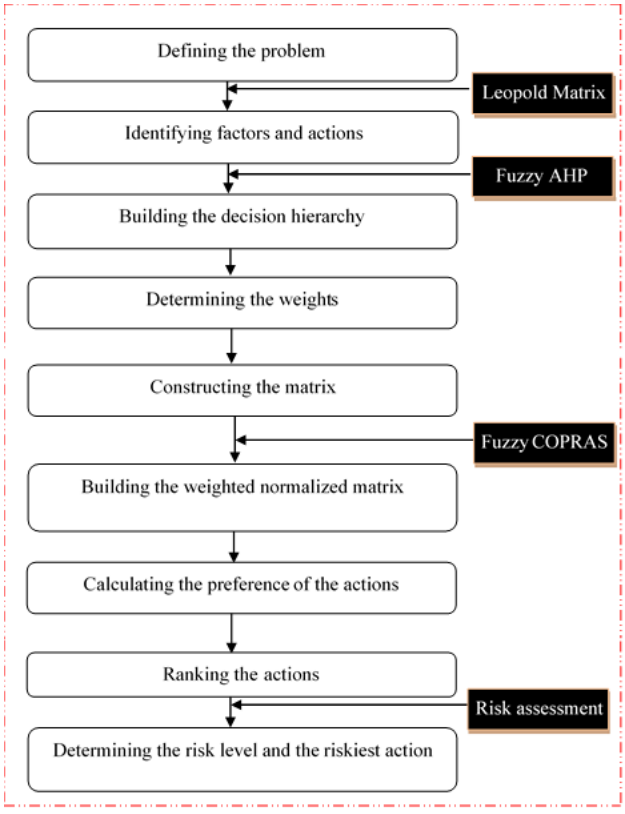


Figure 2. The proposed model

The first stage identifies factors and actions that adversely impact the environment based on the Leopold matrix. Next, the final importance of the factors is obtained by the FAHP process to determine how each factor is influential in the environmental risk assessment process. Then, the fuzzy COPRAS method is employed to understand the most dangerous action. Finally, the risk level is determined in descending order to concentrate the financial sources on the riskiest action by preventative measures. The model is schematically depicted in Figure 2. As shown in the figure, the proposed model uses a four-stage process to evaluate different ecological risks and select the best preventive measure. This procedure reduces the waste of resources including time and finance.

The proposed model takes into account both positive and negative effects, including all possible economic, social, and environmental impacts, of mine development. This model provides a golden opportunity for decision-makers to review a comprehensive evaluation of mine development. This model also provides all the information required for decision-making.

Table 2. Linguistic variables for the evaluation of the criteria

Linguistic variable	Fuzzy number	Fuzzy scale	Triangular fuzzy reciprocal scale
Extreme importance (EXI)	9	(8,9,10)	(1/10,1/9,1/8)
Intermediate (IEXI)	8	(7,8,9)	(1/9,1/8,1/7)
Very strong importance (VSI)	7	(6,7,8)	(1/8,1/7,1/6)
Intermediate (IVSI)	6	(5,6,7)	(1/7,1/6,1/5)
Strong importance (SI)	5	(4,5,6)	(1/6,1/5,1/4)
Intermediate (ISI)	4	(3,4,5)	(1/5,1/4,1/3)
Moderate importance (MI)	3	(2,3,4)	(1/4,1/3,1/2)
Intermediate (IMI)	2	(1,2,3)	(1/3,1/2,1)
Equal importance (EI)	1	(1,1,1)	(1,1,1)

4. Application of the proposed model

4.1. An illustrative example

A real-world case is investigated to show the possible use of the proposed model. The Sangan iron mine is among Iran's primary iron resources. This mine is located in northeast Iran, 308 km southeast of Mashhad city. Figure 3 shows the location and geography of the mine. The mine's resource involves a magnetite skarn, an iron-oxide-type resource. The total geological reserve of the mine is approximately estimated at 1.2 billion tons with an average grade of 50 percent Fe_3O_4. The design of this open pit mine is based on an initial annual production of 3.4 Mt of iron ore concentrate. Based on the mine design report, this



Figure 3. Location of Sangan iron mine

mine will generate about 75 million tons of tailings from the first concentrator plant during the 36-year mine life.

4.2. The implementation of the proposed model

The potential factors and actions are identified in the first stage based on the Leopold matrix. An open-pit mine includes five significant phases: prospecting, exploration, development, exploitation, and reclamation. Each phase is a potential source of miscellaneous environmental risks. Therefore, it is vital to identify all environmental risks in these phases to diminish the risk level. The Leopold matrix is a valuable tool for identifying and classifying the factors and actions that may dramatically impact the existing environment.

By using the Leopold matrix and based on the expert's opinions and literature review (Table 3), fourteen factors are identified and divided into three main factors (Table 4):

- Physical parameters (C1): Soil (C11), Water quality (C12), Dust and Noise (C13), Fly rock (C14), Buildings (C15), Subsidence (C16), and Vibration (C17).
- Social parameters (C2): Safety (C21), Health (C22), Employment (C23), and Land use (C24).
- Ecological parameters (C3): Flora (C31), Fauna (C32), and Waste disposal (C33).

After constructing the decision structure, an expert team with five experts (the demographic information is presented in Table 4) is formed to extract the weight and rating of elements. The specialist team fills out the first questionnaire, as shown in Table 5.

Table 3. The evaluation criteria

Author(s)	Criteria													
	Soil	Water quality	Dust and noise	Fly rock	Buildings	Subsidence	Vibration	Safety	Health	Employment	Land use	Flora	Fauna	Waste disposal
Heydari and Osanloo (2025)	✓	✓	✓	✓		✓	✓					✓	✓	✓
Badri et al. (2011)								✓	✓					
Fan et al. (2022)	✓							✓	✓					
Xu and Cheng (2024)		✓									✓			
Zarubin et al. (2021)	✓	✓	✓								✓			
Timofeeva et al. (2020)										✓				
Koščová et al. (2018)		✓	✓											
Monjezi et al. (2009)		✓	✓	✓			✓			✓				
Cai et al. (2022)														✓
Demková et al. (2019)	✓		✓											✓
Kasap and Subaşı (2017)		✓	✓											
Mohsin et al. (2021)	✓	✓	✓					✓	✓					
Zarshenas and Saeedi (2016)	✓	✓	✓									✓	✓	
Aung et al. (2024)		✓	✓	✓			✓			✓				
Li et al. (2023)					✓									
Florkowska et al. (2021)					✓									

Table 4. The demographic information of the expert team

Characteristics	Explanations	Numbers
Academic qualification	Master of Science	1
	PhD	4
Age	Less than 40 years	1
	Between 40 and 50 years	2
	More than 50 years	2
Experience	Less than 10 years	1
	Between 10 and 20 years	3
	More than 20 years	1
Sex	Male	3
	Female	2

The matrices formed by the expert team are converted into fuzzy matrices to evaluate the decision matrix using Chang's extended method in order to obtain local importance. Table 6 shows the fuzzy matrix concerning physical parameters.

Then, the value of fuzzy synthetic extent concerning the *i*th object is computed as follows:

$$S_1 = (7.33, 9.5, 12) \otimes (0.011, 0.015, 0.023) = (0.083, 0.15, 0.28)$$

$$S_2 = (8, 14, 20) \otimes (0.011, 0.015, 0.023) = (0.091, 0.22, 0.47)$$

$$S_3 = (8.33, 12.5, 17) \otimes (0.011, 0.015, 0.023) = (0.094, 0.198, 0.4)$$

$$S_4 = (5.91, 9.33, 13.5) \otimes (0.011, 0.015, 0.023) = (0.067, 0.148, 0.317)$$

$$S_5 = (5.91, 8.33, 11.5) \otimes (0.011, 0.015, 0.023) = (0.067, 0.132, 0.27)$$

$$S_6 = (4.25, 5.83, 8.5) \otimes (0.011, 0.015, 0.023) = (0.048, 0.092, 0.2)$$

$$S_7 = (2.75, 3.5, 5.5) \otimes (0.011, 0.015, 0.023) = (0.031, 0.055, 0.129)$$

Next, the *V* values calculated using these vectors are presented in Table 7.

Then, priority weights are computed as follows:

$$d'(C1) = 0.728$$

$$d'(C2) = 1$$

$$d'(C3) = 0.928$$

$$d'(C4) = 0.754$$

$$d'(C5) = 0.666$$

$$d'(C6) = 0.457$$

$$d'(C7) = 0.188$$

After the normalization process, relative weights are obtained as follows:

(0.154, 0.212, 0.197, 0.16, 0.141, 0.097, 0.04)

Table 5. The final questionnaire filled out by the expert team

		C1							C2				C3		
		C11	C12	C13	C14	C15	C16	C17	C21	C22	C23	C24	C31	C32	C33
C1	C11	1	IMI**	EI	IMI	EI	EI	MI	EI				EI		
	C12	IMI	1	IMI	IMI	IMI	IMI	MI							
	C13	EI	IMI	1	MI	MI	IMI	IMI							
	C14	IMI	IMI	MI	1	IMI	IMI	MI							
	C15	EI	IMI	MI	IMI	1	MI	IMI							
	C16	EI	IMI	IMI	IMI	MI	1	IMI							
	C17	MI	MI	IMI	MI	IMI	IMI	1							
C2	C21	EI*							1	IMI	MI	MI	IMI		
	C22								IMI	1	IMI	EI			
	C23								MI	IMI	1	IMI			
	C24								MI	EI	IMI	1			
C3	C31	EI							IMI				1	EI	IMI
	C32												EI	1	IMI
	C33												IMI	IMI	1

Notes: * Bold characters indicate the main factors; ** Red color indicates the reciprocal scale.

Table 6. The fuzzy pairwise comparison matrix concerning physical parameters

	C11	C12	C13	C14	C15	C16	C17
C11	(1,1,1)	(1/3,1/2,1)	(1,1,1)	(1,2,3)	(1,1,1)	(1,1,1)	(2,3,4)
C12	(2,3,4)	(1,1,1)	(1,2,3)	(1,2,3)	(1,2,3)	(1,2,3)	(2,3,4)
C13	(1,2,3)	(1/3,1/2,1)	(1,1,1)	(2,3,4)	(2,3,4)	(1,2,3)	(1,2,3)
C14	(1,2,3)	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1,1,1)	(1,2,3)	(1,2,3)	(2,3,4)
C15	(1,1,1)	(1/5,1/4,1/3)	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1,1,1)	(2,3,4)	(1,2,3)
C16	(1,1,1)	(1/6,1/5,1/4)	(1/6,1/5,1/4)	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1,1,1)	(1,2,3)
C17	(1/3,1/2,1)	(1/7,1/6,1/5)	(1/6,1/5,1/4)	(1/5,1/4,1/3)	(1/3,1/2,1)	(1/3,1/2,1)	(1,1,1)

Table 7. *V* values result

	S_1	S_2	S_3	S_4	S_5	S_6	S_7
$V(S_1 \geq \cdots)$		1	1	0.989	0.910	0.667	0.326
$V(S_2 \geq \cdots)$	0.728		0.928	0.754	0.666	0.457	0.188
$V(S_3 \geq \cdots)$	0.798	1		0.816	0.727	0.499	0.195
$V(S_4 \geq \cdots)$	1	1	1		0.928	0.705	0.402
$V(S_5 \geq \cdots)$	1	1	1	1		0.770	0.448
$V(S_6 \geq \cdots)$	1	1	1	1	1		0.687
$V(S_7 \geq \cdots)$	1	1	1	1	1	1	

Table 8. The fuzzy pairwise comparison matrix with regard to social parameters

	C21	C22	C23	C24
C21	(1,1,1)	(1,2,3)	(2,3,4)	(2,3,4)
C22	(1/3,1/2,1)	(1,1,1)	(1,2,3)	(1,1,1)
C23	(1/4,1/3,1/2)	(1/3,1/2,1)	(1,1,1)	(1/3,1/2,1)
C24	(1/4,1/3,1/2)	(1,1,1)	(1,2,3)	(1,1,1)

Table 8 shows the fuzzy pairwise comparison matrix with regard to social parameters.

Similar calculations are accomplished, and the *V* values calculated using these vectors are presented in Table 9.

Table 9. *V* values result

	S_1	S_2	S_3	S_4
$V(S_1 \geq \cdots)$		0.462	0.055	0.404
$V(S_2 \geq \cdots)$	1		0.523	0.969
$V(S_3 \geq \cdots)$	1	1		1
$V(S_4 \geq \cdots)$	1	1	0.550	
$d'(Ci)$	1	0.462	0.055	0.404

After normalizing, relative weights are obtained as follows:

(0.521, 0.24, 0.029, 0.21).

Table 10 shows the fuzzy pairwise comparison matrix with regard to ecological parameters.

Table 10. The fuzzy pairwise comparison matrix with regard to ecological parameters

	C31	C32	C33
C31	(1,1,1)	(1,1,1)	(1/3,1/2,1)
C32	(1,1,1)	(1,1,1)	(1/3,1/2,1)
C33	(1,2,3)	(1,2,3)	(1,1,1)

Similar calculations are accomplished, and the *V* values calculated using these vectors are presented in Table 11.

Table 11. *V* values result

	S_1	S_2	S_3
$V(S_1 \geq \cdots)$		1	1
$V(S_2 \geq \cdots)$	1		1
$V(S_3 \geq \cdots)$	0.391	0.391	
$d'(Ci)$	0.391	0.391	1

After normalizing, relative weights are obtained as follows:

(0.219, 0.219, 0.561).

Table 12 shows the fuzzy pairwise comparison matrix with regard to the primary goal.

Similar calculations are accomplished, and the *V* values calculated using these vectors are presented in Table 13.

After normalizing, relative weights are obtained as follows:

(0.251, 0.553, 0.197).

Table 12. The fuzzy pairwise comparison matrix with regard to the main goal

	C1	C2	C3
C1	(1,1,1)	(1,1,1)	(1,1,1)
C2	(1,1,1)	(1,1,1)	(1,2,3)
C3	(1,1,1)	(1/3,1/2,1)	(1,1,1)

Table 13. *V* values result

	S_1	S_2	S_3
$V(S_1 \geq \cdots)$		1	0.624
$V(S_2 \geq \cdots)$	0.453		0.356
$V(S_3 \geq \cdots)$	1	1	
$d'(Ci)$	0.391	1	0.356

The final weights are calculated by multiplying the local weights with the relative importance of the main criteria as follows:

$$W = (w_{C11}, w_{C12}, w_{C13}, w_{C14}, w_{C15}, w_{C16}, w_{C17}, w_{C21}, w_{C22}, w_{C23}, w_{C24}, w_{C31}, w_{C32}, w_{C33}) =$$
$$(0.039, 0.053, 0.049, 0.04, 0.035, 0.024, 0.01, 0.288, 0.133, 0.016, 0.116, 0.043, 0.043, 0.11).$$

Likewise, the Leopold matrix determines nine actions, including blasting and drilling (A1), surface excavation (A2), mineral processing (A3), product storage (A4), landscaping (A5), waste management (A6), transportation (A7), stabilization (A8), and overburden (A9), as listed in Table 14. The expert team fills in the rating of the actions concerning the factors, as shown in Table 14.

In order to analyze the decision matrix, the primary matrix is transferred into the fuzzy decision matrix, as shown in Table 15.

Then, the weighted decision matrix is obtained by multiplying the values from the fuzzy AHP and those of the fuzzy decision matrix, as listed in Table 16.

According to the fuzzy COPRAS technique, each alternative's cost and benefit indicators are computed. Finally, each option's importance weights and utility degrees are obtained, as depicted in Table 17. From the table, transportation (A7) is the first rank in the list of actions, while overburden (9) is the last.

However, transportation is a major part of mining activities and plays a key role in capital and operational costs. Therefore, the performance evaluation of the transportation system is necessary to control problems, weaknesses, and threats and improve strengths, robustness, and durability.

Table 14. The expert team filled out the second questionnaire

	A1	A2	A3	A4	A5	A6	A7	A8	A9
C11	M	H	H	M	L	VH	H	H	M
C12	VL	M	VH	M	VL	VH	L	VL	VL
C13	H	H	M	VL	M	M	M	VL	L
C14	VH	L	VL	L	VL	VL	VL	VL	VL
C15	H	L	VL	VL	VL	VL	VL	L	VL
C16	VL	VL	VL	VL	L	L	L	VH	VL
C17	H	L	VL	VL	VL	VL	L	M	VL
C21	VH	H	L	L	M	M	M	VH	M
C22	H	H	H	M	M	VH	L	M	M
C23	VL	VH	H	M	VL	H	H	H	H
C24	H	VH	VH	H	VH	VH	L	VH	VH
C31	L	H	H	M	H	H	L	H	VH
C32	L	H	H	M	H	H	L	H	VH
C33	M	VH	VH	L	H	VH	VL	M	VH

Table 15. Fuzzy decision matrix

	A1	A2	A3	A4	A5	A6	A7	A8	A9
C11	(3,5,7)	(5,7,9)	(5,7,9)	(3,5,7)	(1,3,5)	(7,9,10)	(5,7,9)	(5,7,9)	(3,5,7)
C12	(0,1,3)	(3,5,7)	(7,9,10)	(3,5,7)	(0,1,3)	(7,9,10)	(1,3,5)	(0,1,3)	(0,1,3)
C13	(5,7,9)	(5,7,9)	(3,5,7)	(0,1,3)	(3,5,7)	(3,5,7)	(3,5,7)	(0,1,3)	(1,3,5)
C14	(7,9,10)	(1,3,5)	(0,1,3)	(1,3,5)	(0,1,3)	(0,1,3)	(0,1,3)	(0,1,3)	(0,1,3)
C15	(5,7,9)	(1,3,5)	(0,1,3)	(0,1,3)	(0,1,3)	(0,1,3)	(0,1,3)	(1,3,5)	(0,1,3)
C16	(0,1,3)	(0,1,3)	(0,1,3)	(0,1,3)	(1,3,5)	(1,3,5)	(1,3,5)	(7,9,10)	(0,1,3)
C17	(5,7,9)	(1,3,5)	(0,1,3)	(0,1,3)	(0,1,3)	(0,1,3)	(1,3,5)	(3,5,7)	(0,1,3)
C21	(7,9,10)	(5,7,9)	(1,3,5)	(1,3,5)	(3,5,7)	(3,5,7)	(3,5,7)	(7,9,10)	(3,5,7)
C22	(5,7,9)	(5,7,9)	(5,7,9)	(3,5,7)	(3,5,7)	(7,9,10)	(1,3,5)	(3,5,7)	(3,5,7)
C23	(0,1,3)	(7,9,10)	(5,7,9)	(3,5,7)	(0,1,3)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)
C24	(5,7,9)	(7,9,10)	(7,9,10)	(5,7,9)	(7,9,10)	(7,9,10)	(1,3,5)	(7,9,10)	(7,9,10)
C31	(1,3,5)	(5,7,9)	(5,7,9)	(3,5,7)	(5,7,9)	(5,7,9)	(1,3,5)	(5,7,9)	(7,9,10)
C32	(1,3,5)	(5,7,9)	(5,7,9)	(3,5,7)	(5,7,9)	(5,7,9)	(1,3,5)	(5,7,9)	(7,9,10)
C33	(3,5,7)	(7,9,10)	(7,9,10)	(1,3,5)	(5,7,9)	(7,9,10)	(0,1,3)	(3,5,7)	(7,9,10)

Table 16. The weighted decision matrix

	A1	A2	A3	A4	A5	A6	A7	A8	A9
C11	0.022	0.031	0.031	0.022	0.013	0.039	0.031	0.031	0.022
C12	0.008	0.031	0.053	0.031	0.008	0.053	0.018	0.008	0.008
C13	0.049	0.049	0.035	0.009	0.035	0.035	0.035	0.009	0.021
C14	0.040	0.014	0.006	0.014	0.006	0.006	0.006	0.006	0.006
C15	0.035	0.015	0.007	0.007	0.007	0.007	0.007	0.015	0.007
C16	0.004	0.004	0.004	0.004	0.008	0.008	0.008	0.024	0.004
C17	0.010	0.004	0.002	0.002	0.002	0.002	0.004	0.007	0.002
C21	0.288	0.232	0.100	0.100	0.166	0.166	0.166	0.288	0.166
C22	0.107	0.107	0.107	0.077	0.077	0.133	0.046	0.077	0.077
C23	0.002	0.016	0.013	0.009	0.002	0.013	0.013	0.013	0.013
C24	0.094	0.116	0.116	0.094	0.116	0.116	0.040	0.116	0.116
C31	0.015	0.035	0.035	0.025	0.035	0.035	0.015	0.035	0.043
C32	0.015	0.035	0.035	0.025	0.035	0.035	0.015	0.035	0.043
C33	0.064	0.110	0.110	0.038	0.089	0.110	0.017	0.064	0.110

Table 17. The problem solution results

	A1	A2	A3	A4	A5	A6	A7	A8	A9
P_i	0.406	0.386	0.273	0.216	0.253	0.365	0.243	0.385	0.264
R_i	0.348	0.414	0.381	0.240	0.347	0.393	0.179	0.343	0.375
Q_i	0.708	0.641	0.549	0.655	0.557	0.632	0.832	0.692	0.545
N	85.188	77.050	66.029	78.807	66.981	76.067	100.000	83.281	65.492
Rank	2	5	8	4	7	6	1	3	9

5. Sensitivity analysis

A sensitivity analysis is employed based on the effect of changing the weights of sub-criteria on the ranking results of the investigated risks to indicate whether the ranking results are altered or not. This process illustrates how the relative changes in each criterion can affect the overall output. From accomplishing this procedure, the most and least sensitive criteria are extracted. Hence, the importance weights are changed in a 50% interval. Then, the weights are normalized, and finally, the candidate risks are prioritized by using the process described in the fuzzy COPRAS method. The results obtained from the evaluation process based on the main and sub-criteria are depicted in Figures 4–5.

The obtained results indicated in Figures 4–5 show that the importance weights are robust to rank the candidates. In addition, the weights of attributes are increased and decreased by 50%. After normalizing the weights of attributes, the procedure of the proposed method is applied to indicate its effect on the ranking results. Therefore, the sensitivity analysis shows that the ranking of candidates is not sensitive to the weights of attributes. Hence, the transportation action is selected as the first candidate. Consequently, we conclude

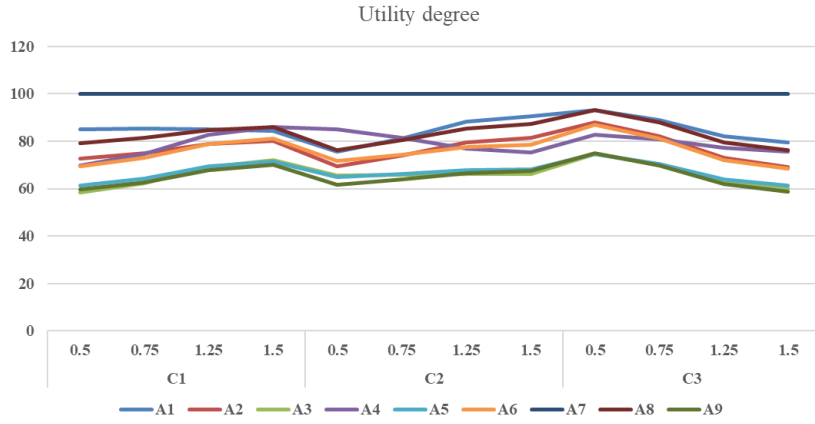


Figure 4. Sensitive analysis of the utility degree based on the main-criteria changes

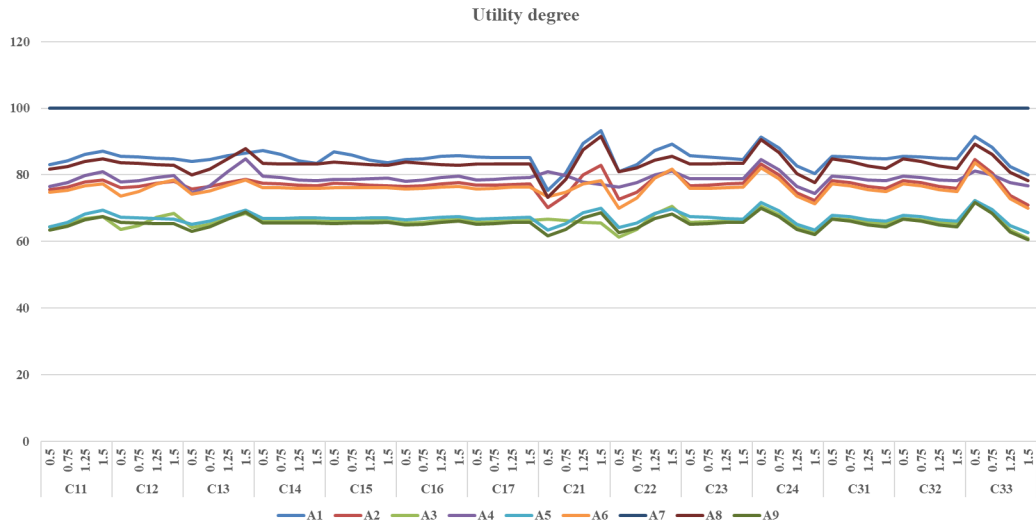


Figure 5. Sensitive analysis of the utility degree based on the sub-criteria changes

that the candidate rates do not change in the range of $0.05 \leq w_j \leq 1.5$.

6. Results

According to the proposed model, the primary classification is based on the three main groups that were defined previously: physical parameters, social parameters, and ecological parameters. Several sub-classes are identified to extract the relative importance of each group's criteria. Fuzzy logic is employed in the evaluation process to take into account the uncertainty involved in the decision process. A mining project is illustrated to investigate the potential application of the proposed approach. However, mining operations directly influence the environment and generate specific adverse environmental effects, e.g., air, water, soil pollution, and health problems.

When considering the criteria mentioned above, it is clear that it is necessary to implement ecological risk management in mining operations by (i) identifying the sources of ecological pollution risk from mining operations, (ii) conducting the "Conservation and Management of Resources" tasks; (iii) accomplishing the measures adopted by the Iranian Department of Environment. These mechanisms aim to reduce the ecological pollution rate by considering the main limitations of time and finance. The results of the obtained model analysis are presented in Table 15. It can be shown that transportation (A7) is the most critical risk, and overburden (9) is the least vital risk. This demonstrates that the risk pertaining to transportation plays the most crucial role in mining operations. Therefore, preventive measures should be considered to eliminate or diminish the transportation risk.

7. Conclusions

The Leopold matrix is a quantifiable analysis of mining operations, especially in investigating the environmental impacts. However, this method cannot model the vagueness imposed by the mining projects. On the other hand, fuzzy logic is capable of modeling uncertainty. Likewise, the MCDM techniques can take into account both intangible and tangible components. This paper uses the fuzzy AHP to determine the importance weights of the factors identified by the Leopold matrix and the fuzzy COPRAS to calculate the actions proposed by the Leopold matrix. Finally, the model is validated by a confirmed case of the Sangan iron mine. The results demonstrate that the model helps managers understand how an action is essential and the reasons behind why a risk management scenario must be adopted. The uncertainty surrounding future ecological policies and trajectories further highlights the necessity for monitoring in adaptive scenarios. The research highlights the significance of strong modeling methods in guiding decision-making and the need for proactive actions to mitigate the effects of ecological hazards on projects. Science and engineering researchers can apply the proposed model to formulate and solve the risks imposed by projects.

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