The selection of an appropriate method for Gazik Granite Quarry mine using a hybrid multi-criteria decision-making method

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ABSTRACT

One of the crucial stages in the operation of quarry exploitation is the selection of an appropriate mining method because the lack of attention to this issue may bring about many problems in the process of mining, leading to extra charges incurred to the mine owner or the possible drop in the quality or quantity of the mine product. The adoption of the appropriate method of quarry mining, given the various interacting factors involved, requires a multi-criteria decision-making method. This paper makes use of the hybrid AHP-ELECTRE model to examine the conventional quarry mining methods including Diamond Wire Sawing, Blasting, Feathers, and Wedge as well as the expansive agents such as KATROCK and FRACT.AG in the granite quarry of Gazik located in the South Khorassan Province, taking into consideration various factors such as the gross profit increase, safety, quality, decrease of adverse environmental effects, wastage, and the reduction of mining time. In this model, the weights of the items were applied by the AHP method, and the items were assessed through non-rank comparisons so that, finally, the Diamond Sawing Blasting was chosen as the most appropriate method of Gazik granite quarry mining based on the ELECTRE model. Such studies can aid in managing the mining costs to decrease, which can lead to the profitability of the quarries.

Keywords: Mining method, Granite quarry, Multi-criteria decision-making, Hybrid AHP-ELECTRE model

1. Introduction

Selection of the appropriate method for quarry mining is of particular importance because if a suitable mining method is not selected, several difficulties arise in extraction operations, additional costs will be imposed on the project and the quality and quantity of the mineral products may be reduced. Advancement of technology and the use of machinery have abolished primary methods in which human resources somehow played a significant role. Therefore, the adoption of a quarry mining method is considered as a strategic decision in terms of economic, technical, and safety aspects because an appropriate selection will lead to more profitability and vice versa, which can even result in the permanent mine closure. In case an inappropriate method is chosen at the onset, the subsequent modifications will be hard and costly. In this regard, the method of quarry mining should be chosen based on the features of the quarry and its lateral conditions. Given the geometrical and geological complexities of mineral resources, one single mining method cannot be used for all mineral resources, so for a specific reserve, its mining method must be applied. There are several methods used for quarry mining including Feathers and Wedge, Havage, Steel Wire Sawing, Diamond Wire Sawing, Blasting (weak explosives) as well as the expansive agents such as KATROCK and FRACT.AG. Since any of these methods has pros and cons compared to other methods, the adoption of the appropriate method must be done according to the executive conditions, methods specifications, and mineral deposit conditions. Several studies have been conducted on the selection of the mining method by [1-39], but regarding the selection of the quarry mining method, [36, 40-42] have conducted their researches. The above-mentioned studies have all had their defects so that none of them has offered a comprehensive mining method. In order to remove such defects, the hybrid multi-criteria decision-making models can be used to appropriately select a quarry mining method. The current paper utilizes the hybrid AHP-ELECTRE model as the most suitable method of quarry mining in the region of South Khorassan. To this end, some criteria such as gross profit, quality, safety, etc. were considered, and since the ELECTRE method cannot determine the significance of the criteria, and the weights of the criteria would remain unknown, the AHP method was used to determine the weights of the criteria. Next, each item was assessed based on every criterion, which led to the adoption of the best item through the use of the ELECTRE method.

2. Case Study

The Iranian quarries have a wide variety in terms of material and color. One of the most important quarries is granite. The South Khorassan Province, with more than 63 million tons of granite, is considered as one of the poles of these types of quarries in Iran. Given the importance of granite mines in the mineral economy of the South Khorassan Province, as well as the abundance of such mines in the province and the high costs of mining, the adoption of an appropriate mining method at the Gazik granite quarry of the South Khorassan is the objective of the current study. Since there are many problems in the exploitation of this mine, the adoption of an appropriate mining method based on scientific criteria can manage the related costs. Due to this issue, the data on this mine was examined upon being updated through the hybrid AHP-ELECTRE.

3. Hybrid AHP-ELECTRE Multi-Criteria Decision-Making Model

The ELECTRE model is a powerful multi-criteria decision-making...
method for selecting the best option out of several ones, but its major defect is that it cannot determine criterion weights. In order to overcome this problem, the hybrid AHP-ELECTRE model can be used, where the criterion weights and the best option are respectively determined through the AHP and ELECTRE methods.

3.1. AHP Method

The Analytical Hierarchy Process (AHP) is an effective multi-criteria decision-making method first posed by Saaty in 1980 [43]. It was designed to assist planners in resolving complex decision-making problems where a large number of planners participate, and several criteria exist in several specific periods [44]. The AHP is an MCDM method that is easy to use and flexible [45]. It allows complex problems with multiple and sometimes conflicting criteria to be addressed. It is suited to some domains and to different problems since it relies on the innate human propensity to conduct comparison [46]. This method, due to its powerful theoretical base, high accuracy, ease of use, reliability, and precise results is considered one of the most prevalent multi-criteria decision-making methods. The AHP method seeks to determine the relative significance of criteria or items based on a binary comparison of the decision-making components while considering the items and criteria. In order to calculate weight in the hierarchy analysis, the elements of each level are compared to the higher ones in a binary manner, followed by the formation of a binary comparison matrix.

The AHP procedure for accounting relative weights involves three essential steps: defining the effective criteria, establishing a pairwise comparison matrix, and precise results is considered one of the most prevalent multi-criteria decision-making methods. The AHP method seeks to determine the relative weights of matrix A are obtained. The scalar value of the criteria is the number of the criteria.

Finally, after the pairwise comparison between the criteria, calculate the relative weights of certain criteria. All the stages of the ELECTRE technique are based on a harmonious as well as a non-harmonious collection, due to which it is referred to as coordination analysis.

The ELECTRE (Elimination Et Choice in Translating to Reality) approach was first introduced by Benayoun, Roy, and Sussman in 1968 [50]. The method was later developed by Bernard Roy [51, 52]. It is a multi-criteria decision-making procedure that can be applied when a set of alternatives must be ranked according to a set of criteria reflecting the decision maker’s preferences. The relationships between the alternatives and the criteria are described using the attributes referred to as the aspects of the alternatives that are relevant according to the established criteria [53, 54]. That is, this method is based on the study of outranking relations, exploiting notions of concordance [51, 55-56]. These outranking relations are built in such a way that it is possible to compare alternatives [57].

3.2. ELECTRE Method

The ELECTRE (Elimination Et Choice in Translating to Reality) approach was first introduced by Benayoun, Roy, and Sussman in 1968 [50]. The method was later developed by Bernard Roy [51, 52]. It is a multi-criteria decision-making procedure that can be applied when a set of alternatives must be ranked according to a set of criteria reflecting the decision maker’s preferences. The relationships between the alternatives and the criteria are described using the attributes referred to as the aspects of the alternatives that are relevant according to the established criteria [53, 54]. That is, this method is based on the study of outranking relations, exploiting notions of concordance [51, 55-56]. These outranking relations are built in such a way that it is possible to compare alternatives [57].

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In this step, the values $X_{ij}$ of the decision matrix must be normalized to a scale comparable to $t_{ij}$ so that the elements become unit-free. The process is to transform different scales and units among various criteria into common measurable units to allow comparisons across the criteria. Several normalization techniques have been proposed by past researchers to transform the different units into dimensionless values. In this research, the norm technique (Eq. 9) is used for computing element $t_{ij}$ of the normalized decision matrix, which is given as the normalized decision matrix (R).

Step 2: Normalize the decision matrix.

In this step, the values $X_{ij}$ of the decision matrix must be normalized to a scale comparable to $t_{ij}$ so that the elements become unit-free. The process is to transform different scales and units among various criteria into common measurable units to allow comparisons across the criteria. Several normalization techniques have been proposed by past researchers to transform the different units into dimensionless values. In this research, the norm technique (Eq. 9) is used for computing element $t_{ij}$ of the normalized decision matrix, which is given as the normalized decision matrix (R).

\[ R = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{bmatrix} \]  

(8)

Step 3: Establish the criteria weighted matrix.

It cannot be assumed that each evaluation criterion is of equal importance because the evaluation criteria have various meanings.
Therefore, the weight of the criteria must be calculated. The weight value indicates the relative importance of each criterion, given as W:

\[
W = \begin{bmatrix}
    w_1 & 0 & \cdots & 0 \\
    \vdots & w_2 & \ddots & \vdots \\
    0 & \cdots & \cdots & w_n
\end{bmatrix}
\]  

(10)

where; \( w_i \) represents the importance weight of criterion \( C_i \).

Step 4: Compute the normalized weighted decision matrix.

By determination of the weight of each criterion, the weighted normalized decision matrix (V) can be obtained as follows:

\[
V = W \times R = \begin{bmatrix}
    v_{11} & \cdots & v_{1n} \\
    \vdots & \ddots & \vdots \\
    v_{m1} & \cdots & v_{mn}
\end{bmatrix}
\]

(11)

where; \( v_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}} \)

Step 5: Determine the concordance and discordance sets

By comparison of all source pairs in each criterion, concordance and discordance sets are generated.

The concordance set \( S_{ke} \) of \( A_k \) and \( A_e \) \((k, e = 1, 2, \ldots, m, k \neq e)\) is composed of all the criteria for which \( A_k \) is preferred to \( A_e \). The discordance set \( I_{ke} \) is the complementary set of \( S_{ke} \).

\[
S_{ke} = \left\{ j \mid v_{kj} \geq v_{ej} \right\}
\]

(12)

\[
I_{ke} = \left\{ j \mid v_{kj} < v_{ej} \right\}
\]

(13)

Step 6: Calculate the concordance matrix:

The relative value of the concordance sets is measured by means of the concordance index. The concordance index is equal to the sum of the weights associated with those criteria and relations which are contained in the concordance sets. Therefore, the concordance index \( C_{ke} \) between the pair of alternatives \( k \) and \( e \) is defined as:

\[
c_{ke} = \sum_{j \in S_{ke}} w_j
\]

(14)

where \( \sum_{j=1}^{n} w_j = 1 \); therefore, \( C_{ke} \) concordance matrix elements are calculated using the formula:

\[
c_{ke} = \sum_{j \in S_{ke}} w_j
\]

(15)

The concordance index lies between 0 and 1 \((0 \leq C_{ke} \leq 1)\).

The concordance matrix is calculated as below:

\[
C = \begin{bmatrix}
    c_{11} & \cdots & c_{1m} \\
    \vdots & \ddots & \vdots \\
    c_{m1} & \cdots & c_{mm}
\end{bmatrix}
\]

(16)

Step 7: Calculate the discordance matrix.

The discordance index \( d_{ke} \) is the relation of the largest difference overall discordant criteria to the largest difference over all the criteria between the two alternatives and is calculated using the formula:

\[
d_{ke} = \frac{\max_{j \in I_{ke}} |v_{kj} - v_{ej}|}{\max_{j \in S_{ke}} |v_{kj} - v_{ej}|}
\]

(17)

and \((0 \leq d_{ke} \leq 1)\)

The discordance matrix is calculated as below:

\[
D = \begin{bmatrix}
    - & d_{12} & \cdots & d_{1m} \\
    d_{21} & - & \cdots & d_{2m} \\
    \vdots & \vdots & \ddots & \vdots \\
    d_{m1} & \cdots & d_{m(m-1)} & -
\end{bmatrix}
\]

(18)

It is to be noted that the data available in the agreement matrix has a marked difference from the data in the opposed matrix so that they are complements. The weight differences are obtained by the agreement matrix while the differences among the specified amounts are obtained through the opposed matrix.

Step 8: Determine the concordance dominance matrix:

This matrix can be calculated with the aid of a threshold value for the concordance index. \( A_k \) will only have a chance of dominating \( A_e \) if its corresponding concordance index \( C_{ke} \) exceeds at least a certain threshold value \( \bar{C} \) i.e., \( C_{ke} \geq \bar{C} \), and

\[
\bar{C} = \frac{\sum_{k=1}^{m} \sum_{e=1}^{m} c_{ke}}{m(m-1)}
\]

(19)

In the sixth step, the way of calculating the agreement index of \( C_{ke} \) was expressed. Now, a specified amount will be determined for the agreement index known as the agreement boundary and will be shown by \( c \). If \( C_{ke} > c \), the preference of \( k \) option over \( e \) is acceptable; otherwise, there is no such a preference over \( e \) by \( k \).

On the basis of the threshold value, a Boolean matrix \( F \) can be constructed, the elements of which are defined as:

\[
f_{ke} = \begin{cases}
    1 & C_{ke} \geq \bar{C} \\
    0 & C_{ke} < \bar{C}
\end{cases}
\]

(20)

Then, each element of I on the matrix \( F \) represents the dominance of one alternative with respect to another one.

Step 9: Determine the discordance dominance matrix

This matrix is constructed in a way analogous to the \( F \) matrix on the basis of a threshold value \( d \) to the discordance indices.

\[
d = \frac{\sum_{k=1}^{m} \sum_{e=1}^{m} d_{ke}}{m(m-1)}
\]

(21)

As mentioned in the seventh step, the less the disagreement index \( (C_{ke}) \), the better; because the amount of disagreement implies the preference of \( k \) over \( e \). If \( d_{ke} > d \), then the amount of disagreement has been much and it cannot be ignored. So, the elements of \( G_{ke} \) of the discordance dominance matrix \( G \) are calculated as:

\[
g_{ke} = \begin{cases}
    1 & d_{ke} > d \\
    0 & d_{ke} \leq d
\end{cases}
\]

(22)

Also, the unit elements in the \( G \) matrix represent the dominance relationships between any two alternatives.

Step 10: Determine the aggregate dominance matrix.

This step is to calculate the intersection of the concordance dominance matrix \( F \) and discordance dominance matrix \( G \). The resulting matrix, called the aggregate dominance matrix \( H \), is defined by means of its typical elements \( h_{ke} \) as:

\[
h_{ke} = f_{ke} \cdot g_{ke}
\]

(23)

Step 11: Determine the best alternative

The aggregate dominance matrix \( H \) gives the partial-preference ordering of the alternatives. If \( h_{ke} = 1 \), then \( A_k \) is preferred to \( A_e \) for both the concordance and discordance criteria (i.e., the preference exceeds the agreement boundary while the disagreement and loss are less than the disagreement boundary), but \( A_k \) still has the chance of being dominated by the other alternatives. So, there should be an option that is more probable to dominate than to be dominated, which can lead to the ranking of the options.

4. Introduction to Quarry Mining Methods

There are several methods used for quarry mining including Feathers and Wedge, Blasting, expansive chemical agents, Diamond Wire Sawing, Steel Wire Sawing, Havage, Flame-Jet drilling, etc. In the current study, the methods of Feathers and Wedge, Diamond Wire Sawing, Blasting, and expansive agents (KATROCK and FRACT) have been assessed. Below, you can see a summary of each method.
4.1. Feathers and Wedge

The Feathers and Wedge method is an old method for extracting stone blocks. First, a series of holes are drilled along the intended line of fracture. The diameter, depth, and a number of these holes depend on the quality of the stone. The closer the holes are to each other and the deeper they are, the easier the separation would be. After drilling the holes, two metal blades and one hard metal wedge are placed in each hole. This way, the wedge is first put into the position using a light hammer. Next, with a 10-kg mallet, the wedge is hit on until the stone cracks, which leads to obtaining a stone block upon the expansion of the fractures.

4.2. Diamond Wire Sawing

The first unit of Diamond Wire Sawing was established in the Carrara mine. Then on, the method has undergone quick advancement regarding the equipment and parts of the wire. In this method, first, three holes, perpendicular to one another (one vertical and two horizontal ones), are made using a Russell machine or Wagon Drill. Then, in order to cut the bottom, from inside the two horizontal holes, a diamond wire attached to a wheel passes, which moves non-stop on the stone towards a definite direction and is cooled down by water during the operation, making a groove in the stone. This way, the stone is cut. After cutting the bottom, the side and back parts are cut similarly, and the stone is removed off the work bed. During the cutting operation, the machine moves away from the work bed as it goes on the track, keeping the wire pulled.

4.3. Blasting Method

In the method of extracting blocks using blasting, horizontal and vertical holes are first drilled. Then, using special explosives and a detonating fuse, the blasting is done and the block is separated from the mass of stone. The main difference between blasting in quarries and usual blasting lies in the fact that in the former, the fracture must be made in a specific direction without damaging the neighboring stones.

4.4. Expansive Chemical Agents

One conventional mining method in Iran is the use of various types of expansive agents. These materials are increasingly used in quarries instead of inflammable substances. The explosive power of these materials is not equal to that of black powder, dynamite, and ANFO. They function like Feathers and Wedge. To use the materials, some parallel holes must be drilled in the stone. Then, the intended material is mixed with water to form grout. The obtained grout is poured into the holes, which expands several times its size due to the hydration effect, leading to the final crack of the stone and the separation of the block.

5. Effective Criteria in Selecting Granite Quarry Mining

Some factors such as gross profit, quality, safety, time, environmental effects, and wastage are important and must be considered in the quarry mining methods, which can be classified into qualitative and quantitative groups. Some of these criteria have positive and some others have negative effects on the selection of the mining method. For example, the environmental factor could have negative impacts and the safety factor could have positive impacts on the selection. The qualitative and quantitative status of the factors, along with their positive or negative effects, is shown in Table 2. Below, each method is explained with regard to the criteria.

<p>| Table 2. Effective Criteria for quarry mining method selection |
|-----------------------------------|--------------------|----------------|----------------|----------------|</p>
<table>
<thead>
<tr>
<th>Criterion</th>
<th>Gross profit</th>
<th>Time</th>
<th>Waste rock production</th>
<th>Safety</th>
<th>Stone quality</th>
<th>Environmental Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
<td>Quantitative</td>
<td>Qualitative</td>
<td>Qualitative</td>
<td>Qualitative</td>
<td>Qualitative</td>
<td>Qualitative</td>
</tr>
<tr>
<td>Type of criteria</td>
<td>Positive</td>
<td>Negative</td>
<td>Negative</td>
<td>Positive</td>
<td>Positive</td>
<td>Negative</td>
</tr>
</tbody>
</table>

• Gross Profit (cost-income)

Given one block with three free surfaces, for any of the methods of Diamond Wire Sawing, Feathers and Wedge, Blasting, KATROCK, and FRAC EXPANSIVE agents, the extraction cost and the income from selling the stone blocks are as shown in the following table. The costs have been calculated in Table 3 according to the average costs obtained from some active mines in Iran.

<table>
<thead>
<tr>
<th>Table 3. The gross profit from each method is based on the income from selling one cubic meter of stone block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost (Rial/m²)</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Drilling Cost</td>
</tr>
<tr>
<td>Cost of consumables</td>
</tr>
<tr>
<td>Cutting cost</td>
</tr>
<tr>
<td>The cost of machinery</td>
</tr>
<tr>
<td>Waste handling cost</td>
</tr>
<tr>
<td>Total cost</td>
</tr>
<tr>
<td>Price</td>
</tr>
<tr>
<td>Gross profit</td>
</tr>
</tbody>
</table>

| *18=150000Rials |

• Time

If one block is considered with the freedom degree of 3 with the same dimensions, given the fact that in the parallel-holes method, on average, in every 10 centimeters, one hole is drilled, in each of the non-free dimensions of the block, 10 one-meter holes, a total of 30 meters of drilling will be required. Should the drilling time of each meter by five minutes, the total drilling time will be 150 minutes. The time required for filling the holes with expansive agents is usually 30 minutes and the waiting time required for filling the block is 15 minutes. Therefore, the total time required for producing one cubic meter of block in the two methods is 19 and 13 hours. In the Wire Sawing method, drilling 3 conductor one-meter holes will take 15 minutes and the time required for the passage of the wire will be 30 minutes. Given the average cutting speed of one square meter per hour, the total time of the block extraction in this method will be 4 hours. Yet, it should be mentioned that the production time in these three methods is not exactly in the aforementioned ratio, and may vary due to the aeromechanics features of stone in various mines. In the Feathers and Wedge Blasting methods, 30 minutes must be drilled in three non-free dimensions of the stone, which, given the time required for drilling every meter, will take 150 minutes to complete the drilling operation. Moreover, given the fact that a total of 3 hours is required for cracking the stone, the extraction of one cubic meter needs 5.5 hours in this method. Also, given the time required for filling each hole with explosives is 5 minutes, 2.5 hours is required for filling 30 holes. Therefore, in the Blasting method, 5 hours is required to extract a cubic meter of a block. The time required for extracting one cubic meter of stone in different methods is shown in Table 4.

• Waste Rock Production

In case mineral reserves are considered as a national capital so that waste rocks of mining are looked at as a waste of capital, the waste rocks become prominent factors to be considered for the selection of a mining method. One type of such waste rocks produced in the quarry mining is the waste rocks produced in the quartzes at Blasting and Feathers Wedge methods which damage the rock at the time of cutting. Given the mechanism of mining in the Diamond Wire Sawing and Expansive Agents, the waste rocks produced in these methods are less than that produced in traditional methods. Considering the quality of production, this criterion can be considered as a qualitative one. The results obtained from the qualitative comparison of the amount of waste rock produced from one meter of rock in various methods are shown in Table 4.

• Safety

Many of the people who have used chemical expansive agents have...
suffered from pulmonary and eye discomfort. Although the direct effect of using such agents on the aforementioned discomforts has not been confirmed yet, the low quality of production and use of harmful materials for the sake of the low cost of production can cause these illnesses. Moreover, the possibility of producing toxic gases at the time of using the non-standard chemicals cannot be ignored. Due to the low quality of some of these materials, in warm weather and especially at the holes drilled in the stones which have long been exposed to sunlight, these chemicals are quickly enlarged, functioning almost as explosives do, which leads to throwing the stones. The Blasting method also has the least advantage because of toxic gas emissions resulting from the explosives decomposition and stone-throwing. The results of studying safety issues for each of the methods are presented in Table 4.

- Stone Blocks Quality

The product obtained from the Diamond Wire Sawing is so different from that of traditional methods that the transportation cost decreases, the production efficiency increases in stone factories, and the transportation and work bed are facilitated. Given the fact that the extracted block from the Diamond Wire Sawing method does not require an initial cutting, the final production cost decreases in this method. In other words, it could be stated that the higher the quality of the extracted block, the more its sale price will be. The extracted block in the Blasting method is of the least quality while the quality of the obtained block through expansive chemicals and the Feathers and Wedge method is in the middle of those of Diamond Wire Sawing and Blasting methods. The results of the examination of the quality in each method are presented in Table 4.

- Environmental Problems

Generally speaking, any mineral operation impacts at least one of the environmental elements such as water, soil, and weather. Given the environmental problems which are incurred by quarry mining methods, the points were allocated to any of the methods as shown in Table 4.

<table>
<thead>
<tr>
<th>Table 4. Decision matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternative</td>
</tr>
<tr>
<td>Expansive KATROCK</td>
</tr>
<tr>
<td>agent FRACT</td>
</tr>
<tr>
<td>Blasting</td>
</tr>
<tr>
<td>diamond wire sawing</td>
</tr>
<tr>
<td>Feathers and wedge</td>
</tr>
</tbody>
</table>

6. The Selection of the Quarry Mining Method Using the Hybrid AHP-ELECTRE Model

First, develop a hierarchy by the three major levels of the goal, the objectives, and the alternatives. The hierarchy for the selection of the quarry mining method selection is illustrated in Figure 1. Then, the decision-making matrix showing the options in terms of various factors must be formed. To this end, given the available quarry mining methods, five options of Feathers and Wedge, Diamond Wire Sawing, FRACT, and KATROCK expansive agents, as well as Blasting, were assessed in terms of six factors, i.e. the gross profit, quality, safety, time, waste rock amount and environmental effects for which the results are shown in Table 4.

In the next step, the qualitative criteria must be turned into quantitative ones. So, quality, safety, environmental effects, and waste rocks expressed qualitatively must be turned into quantitative amounts based on Table 5. The results of this are presented as the modified decision matrix in Table 6. Then, the matrix must become dimensionless using Eq. (10), being turned into numbers between zero and one. The normalized decision matrix (dimensionless) is presented in Table 7.

Table 5. Linguistic variables for the ratings

<table>
<thead>
<tr>
<th>Linguistic variables</th>
<th>Numeric variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive criteria (+)</td>
<td>Negative criteria (-)</td>
</tr>
<tr>
<td>Very Low</td>
<td>1</td>
</tr>
<tr>
<td>Low</td>
<td>3</td>
</tr>
<tr>
<td>Medium</td>
<td>5</td>
</tr>
<tr>
<td>High</td>
<td>7</td>
</tr>
<tr>
<td>Very High</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 6. Decision matrix expressed in numeric variable

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Gross profit (+)</th>
<th>Stone quality (+)</th>
<th>Safety (+)</th>
<th>Time (-)</th>
<th>Environmental Problems (-)</th>
<th>Waste rock production (+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansive KATROCK</td>
<td>4084800</td>
<td>Low</td>
<td>Low</td>
<td>19</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>agent FRACT</td>
<td>3618000</td>
<td>High</td>
<td>Medium</td>
<td>13</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Blasting</td>
<td>2287200</td>
<td>Low</td>
<td>Low</td>
<td>5</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>diamond wire sawing</td>
<td>399200</td>
<td>Very High</td>
<td>High</td>
<td>4</td>
<td>Low</td>
<td>Very Low</td>
</tr>
<tr>
<td>Feathers and wedge</td>
<td>3868800</td>
<td>Low</td>
<td>Low</td>
<td>5.5</td>
<td>Very Low</td>
<td>High</td>
</tr>
</tbody>
</table>

In the next step, given the fact that the ELECTRE method is not able to determine the weight or significance of the criteria, the AHP method is used to determine the significant coefficients of the criteria. To this end, the criteria are compared in pairs, and upon their comparison, the numerical points (paired comparison matrix) will be allocated based on the lingual variables presented in Table 1, the results of which by the eigenvector method

Table 7. Normalized decision matrix

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Gross profit (+)</th>
<th>Stone quality (+)</th>
<th>Safety (+)</th>
<th>Time (-)</th>
<th>Environmental Problems (-)</th>
<th>Waste rock production (+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansive KATROCK</td>
<td>0.69</td>
<td>0.24</td>
<td>0.25</td>
<td>0.77</td>
<td>0.22</td>
<td>0.38</td>
</tr>
<tr>
<td>agent FRACT</td>
<td>0.68</td>
<td>0.56</td>
<td>0.42</td>
<td>0.53</td>
<td>0.38</td>
<td>0.53</td>
</tr>
<tr>
<td>Blasting</td>
<td>0.28</td>
<td>0.24</td>
<td>0.25</td>
<td>0.20</td>
<td>0.23</td>
<td>0.23</td>
</tr>
<tr>
<td>diamond wire sawing</td>
<td>0.68</td>
<td>0.72</td>
<td>0.59</td>
<td>0.16</td>
<td>0.53</td>
<td>0.68</td>
</tr>
<tr>
<td>Feathers and wedge</td>
<td>0.47</td>
<td>0.24</td>
<td>0.59</td>
<td>0.22</td>
<td>0.68</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Table 8. Pairwise comparison matrix for quarry mining methods criteria

<table>
<thead>
<tr>
<th></th>
<th>Gross profit</th>
<th>Stone quality</th>
<th>Safety</th>
<th>Time</th>
<th>Environmental Problems</th>
<th>Waste rock production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross profit</td>
<td>1</td>
<td>3</td>
<td>7</td>
<td>5</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>Stone quality</td>
<td>1/3</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Safety</td>
<td>1/7</td>
<td>1/5</td>
<td>1</td>
<td>1/2</td>
<td>2</td>
<td>1/3</td>
</tr>
<tr>
<td>Time</td>
<td>1/5</td>
<td>1/3</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>1/2</td>
</tr>
<tr>
<td>Environmental Problems</td>
<td>1/9</td>
<td>1/7</td>
<td>1/2</td>
<td>1/3</td>
<td>1</td>
<td>1/5</td>
</tr>
<tr>
<td>Waste rock production</td>
<td>1/3</td>
<td>1/2</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>
entitled the criterion weight matrix (W) as follows:

\[
W = \begin{bmatrix}
0.44 & 0 & 0 & 0 & 0 \\
0 & 0.24 & 0 & 0 & 0 \\
0 & 0 & 0.05 & 0 & 0 \\
0 & 0 & 0 & 0.09 & 0 \\
0 & 0 & 0 & 0 & 0.03 \\
0 & 0 & 0 & 0 & 0.15
\end{bmatrix}
\]

Upon the determination of the criterion weight matrix, the normalized weighted decision matrix is obtained via Eq. (11) (Table 9).

In order to specify the best option through the ELECTRE method, the set of concordance and discordance criteria are formed based on Eqs. (19) and (20), the concordance dominance matrix (F), and using Eqs. (21) and (22), the discordance dominance matrix (G) is determined, finally leading to the determination of the ultimate aggregate dominance matrix (H) based on Relation 23.

Table 9. The normalized weighted decision matrix

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Gross profit (+)</th>
<th>Stone quality (+)</th>
<th>Safety (+)</th>
<th>Time (-)</th>
<th>Environmental Problems (-)</th>
<th>Waste rock production (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansive KATROCK</td>
<td>0.217</td>
<td>0.058</td>
<td>0.011</td>
<td>0.070</td>
<td>0.007</td>
<td>0.057</td>
</tr>
<tr>
<td>Blasting</td>
<td>0.121</td>
<td>0.134</td>
<td>0.021</td>
<td>0.048</td>
<td>0.011</td>
<td>0.080</td>
</tr>
<tr>
<td>Diamond wire sawing</td>
<td>0.212</td>
<td>0.172</td>
<td>0.029</td>
<td>0.015</td>
<td>0.016</td>
<td>0.103</td>
</tr>
<tr>
<td>Feathers and wedge</td>
<td>0.205</td>
<td>0.058</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.034</td>
</tr>
</tbody>
</table>

In the end, Table 10 is obtained given the number of the dominated and non-dominated criteria determined by the ultimate aggregate dominance matrix. The criterion which is more dominated than peripheral is considered as preferred, and the rankings of them are shown in Table 10.

As shown in the prioritization of the options, the Diamond Wire Sawing is an appropriate method for Gazik granite quarry mine through the hybrid AHP-ELECTRE model.

Table 10. Selection of the best alternative

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Number of the dominated</th>
<th>Number of the non-dominated</th>
<th>Difference</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansive agent (KATROCK)</td>
<td>1</td>
<td>3</td>
<td>-2</td>
<td>Rank 3</td>
</tr>
<tr>
<td>Expansive agent (FRACT)</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>Rank 2</td>
</tr>
<tr>
<td>Blasting</td>
<td>0</td>
<td>4</td>
<td>-4</td>
<td>Rank 4</td>
</tr>
<tr>
<td>Diamond wire sawing</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>Rank 1</td>
</tr>
<tr>
<td>Feathers and wedge</td>
<td>1</td>
<td>3</td>
<td>-2</td>
<td>Rank 3</td>
</tr>
</tbody>
</table>

7. Conclusion

The selection of an appropriate quarry mining method is of prominent significance. In this regard, considering the complexities existing in the geometric and geological features of mineral resources, one mining method cannot be prescribed for all types of mineral resources. So, given such complexities, any resource demands its appropriate mining method. This is not an exception for quarries too so that the selection of an appropriate quarry mining method can increase the efficiency and national gross production. There are numerous methods for quarry mining, but since each method has its own pros and cons, finding the ideal method requires a close examination of the involved factors. Although many quarry mining methods have been introduced, most of them have defects, lacking a comprehensive model of mining. Of such defects, the lack of involving important criteria in the selection of quarry mining methods, the lack of considering all the available methods, and the significant coefficients of the criteria could be named. Therefore, to overcome the defects, hybrid multi-criteria decision-making can be used to select the appropriate quarry mining method. This paper made use of the hybrid AHP-ELECTRE model in order to select the quarry mining method, which led to the selection of the Diamond Wire Sawing as the best option. The results reveal that mining using the Diamond Wire Sawing, contrary to miners’ belief (of its having costs of personnel, used energy, and materials) is the optimum method.

REFERENCES


