GOSPODARKA SUROWCAMI MINERALNYMI

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# Practical applications from decision-making techniques for selection of suitable mining method in Iran

## Introduction

The basic objective in selecting a method to mine a particular ore deposit is to design an ore extraction system that is the most suitable under the actual circumstances. In order to determine which mining method is feasible, we need to compare the characteristics of the deposit with those required for each mining method; the method(s) that best matches should be the one(s) considered technically feasible, and should then be evaluated economically (Nicholas 1993). Before selection of a mining method, it is important to understand the key characteristics required for each mining method. Parameters, which affect choosing mining methods, are mainly, geometry of deposit (size, shape, depth and so on), geology and hydrology conditions (mineralogy, petrology, uniformity, alteration and weathering and so on), geotechnical properties of rocks and ore (elastic properties, state of stress, consolidation, compaction, competency and other physical properties), economic considerations (tonnage of reserves, production rate, mine life, productivity and mining cost), technological factors (mine recovery, dilution, flexibility, selectivity, concentration of workings, capital, labor and mechanization) and environmental concerns such as ground control, subsidence and atmospheric control (Samimi, Shahriar, Karimi 2004; Hartman 2002).

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The selection of mining method requires the consideration, evaluation and choice of decision variables, a task that is usually undertaken by mining engineers on the basis of experience and intuitive judgment. The complexity of the task means that it is best executed by a person with considerable expertise in the subject. We need to simulate the judgment and expertise of a human expert. From the viewpoint of system theory, mining method selection problem is a complete system. This system has the following characteristics.

— The Mining method selection has multi attribute.
— The Mining method selection has multiple dimensions. The system of mining method selection is composed subsystems and each subsystem consists of its own subsystems. For example, the operation system consists of a mining system, ore dressing system and processing system. Therefore, the system of mining method selection is a large system with multiple dimensions.
— The interactions between subsystems are complex. The subsystems are connected with high complexity, not only in structures but also in content.
— There are many factors affecting the system of mining method selection, like the status of ore-body, the demand of products, industry index etc.
— The environmental conditions should be undertaken for a production with regard ecological considerations. The original object is of the complex geology of ore-body; hence the exploitation process is difficult to describe with the mathematical model.
— Information is generally uncertain. In the exploitation process, for instance, information in technology, economy, geology etc is often undefined.
— The Mining method selection is open system. This selection process frequently exchanges material, energy and information with outside systems.
— The system is dynamic. The system parameters often change in space and time.

Therefore, from the viewpoint of system theory, the mining method selection is an open, dynamic and complex large system (Yaming, Ying, Weixuan 2004). In addition to the importance of the selection; the procedure of decision making is rather confusing and difficult. The difficulty of the mining method selection arises from some basic facts. One of them is the absence of a specific formulation for selecting a mining method. This paper deals with the mining method selection, which based on the MADM methods that is one branch of the Decision theory and presents an Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) as an innovative tools for mining method decision problems.

## 1. Literature review

Researchers have studied on mining method selection problem until now. Several methods have been developed in the past to evaluate suitable mining methods for an ore deposit based on its physical characteristics such as shape, grade and geomechanical properties of the rock [4–29]. Peele (1941), Boshkov and Wright (1973), Morrison (1976), Nicholas (1981) and (1993), Loubscher (1981), Hartman (1987), Marano, Everitt (1987), Bandopadhyay, Venkata Subramanian (1987), Agoshkov (1988), Mutagwaba, Terezopoulos (1994), Pakalnis, Miller, Poulin (1995), Hamrin (1998), Tatiya (1998), Basu (1999), Kahriman, Karadogan (2000) and (2001), Kesimal, Bascetin (2002), Meech, Pakalnis, Clayton (2002), Guray, Celebi, Atalay, Pasamehmetoglu (2003), Wei-Xuan and Yiming (2003) and (2004), Shahriar, Samimi (2003) and (2007), Mihaylov, Bakarjev (2005), Miranda, Almeida, Alencar (2005) and Bascetin (2007) published some papers about mining method selection.

The approach to the selection of mining method can be classified in three groups: qualitative methods, numerical ranking methods (scoring) and decision making models. The classification system proposed by Boshkov and Wright based on Peele, was one of the first qualitative classification schemes attempted for underground mining method selection (Peele, Church 1941). It uses general descriptions of the ore thickness, ore dip, strength of the ore, and strength of the walls to identify common methods that have been applied in similar conditions.

Hartman has developed a flow chart selection process for defining the mining method in 1987, based on the geometry of the deposit and the ground conditions of the ore zone. The classification system proposed by Morrison divides underground mining methods into three basic groups: rigid pillar support, controlled subsidence, and caving. General definitions of ore width, support type, and strain energy accumulation are used as the criteria for determining a mining method. This classification helps to demonstrate the selection continuum, choosing one method over another based on the various combinations of ground conditions (Morrison 1976). The selection of an appropriate mass underground mining method has been presented by Laubscher (Labscher 1981). The selection process is based on his rock mass classification system, which adjusts for expected mining effects on the rock mass strength. Laubscher later has modified the classification to relate his rock mass rating to the hydraulic radius. By including the hydraulic radius, cavability becomes feasible for more competent rock if the area available for undercutting is enough (1990).

The Nicholas (1981) method numerically ranks deposit characteristics of ore geometry and rock mechanic characteristics of the ore zone, footwall and hanging wall. The rankings are then summed together whit the higher rankings being the more favorable or likely mining methods. Later Nicholas made some modification to his selection procedure by introducing a weighting factor in 1993 (Nicholas 1993). The UBC (University of British Columbia) mining method selection algorithm developed by Miller, Pakalnis and Poulin (1995) is a modification to the Nicholas approach, which places more emphasis on stoping methods, thus better representing typical Canadian mining design practices (Miller, Pakalnis, Poulin 1995).

## 2. Decision making theory

Decision-making is commonly explained as a selection process, in which the best alternative is chosen from alternative sets in order to reach an aim or aims. Decision theory, as a specialized field of Operation Research (OR), is the process of specifying a problem or opportunity, identifying alternatives and criteria, evaluating alternatives, and selecting a preferred alternative from among the possible ones. A definition of Decision theory from Society for Judgment and Decision Making (SJDM) is given as: "Decision theory is a body of knowledge and analytical techniques of different degrees of formality designed to help a decision maker choose among a set of alternatives in light of their possible consequences" (Zhifeng 2005).

Decision theory offers a rich collection of techniques and procedures to reveal preferences and to introduce them into models of decision. Decision theory is not concerned with defining objectives, designing the alternatives or assessing the consequences. It was usually assumed known. Given a set of alternatives, a set of consequences and a correspondence between those sets, decision theory offers conceptually simple procedures for choice. By the properties of the problem, there are Multiple Attribute Decision Making (MADM), Multiple Objective Decision Making (MODM), and Multiple Experts Decision Making (MEDM). Figure 1 shows the relationships between these three categories.

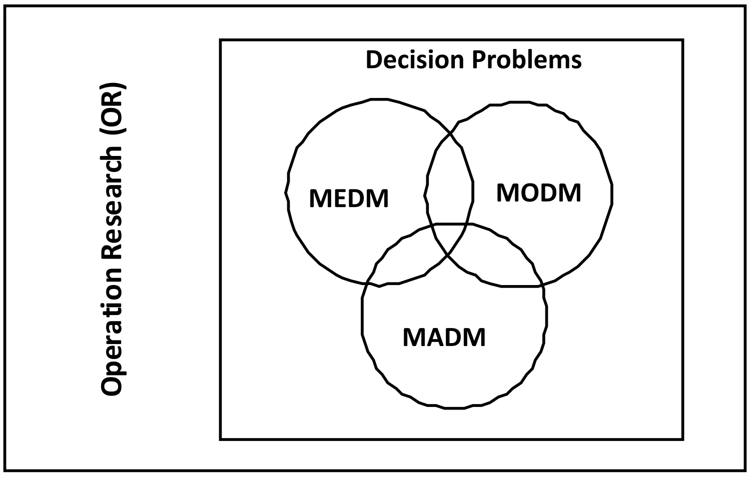


Fig. 1. Category of decision making problems (Zhifeng 2005)

Rys. 1. Kategorie problemów decyzyjnych (Zhifeng 2005)

The Multiple Criteria Decision Making (MCDM) is a well known branch of a major class of decision making. This major class is further divided into Multiple Attribute Decision Making (MADM) and Multiple Objective Decision Making (MODM) (Climaco 1997). The objective of MADM is to select the best alternative from several mutually exclusive alternatives based on their general performance regarding various attributes decided by the decision maker. In MODM the decision maker wants to attain more than one objective or goal in electing the course of action while satisfying the constraints dictated by environment, processes, and resources. The Multiple Experts Decision Making (MEDM) basically solicits opinions from experts and combines these judgments into a coherent group decision (Zhifeng 2005).

From a trade-off point of view, MADM models can be divided into two main categories: non-compensatory and compensatory. Unlike the non-compensatory, the compensatory methods are allowed to take possible attribute trade-offs into consideration. The application of the latter category can be a useful tool for mining method selection problems where interactions between numerous aspects of design selection are typically unavoidable. Depending on the type and the characteristic of the problem a number of compensatory MADM methods have been developed.

Existing methods can be classified into three broad categories: (1) Value measurement models (AHP and MAUT are the best known method in this group), (2) Goal, aspiration and reference level models (Goal programming and TOPSIS are the most important methods that belong to the group) and (3) Outranking models (ELECTRE and PROMETHEE are two main families of method in this group). The focus of this article is on three kinds of compensatory MADM techniques, AHP, TOPSIS and PROMETHEE as a sample of each above mentioned category in order to present the ability of compensatory MADM techniques for mining method selection.

## 3. Analytic Hierarchy Process (AHP)

AHP was developed by Saaty (1980). This method is a procedure that supports a hierarchical structure of the problem, and use pair-wise comparison of all objects and alternative solutions. This method, well known as the analytic hierarchy process (AHP), structures the decision problem into levels corresponding to goals, criteria, sub-criteria and alternatives, making it possible for the decision maker to focus on a smaller set of decisions.

The main feature of AHP is its using the pair-wise comparison to elicit the relative importance of the alternatives in terms of each criterion. It deals with the decision $m_x n$ of dimension matrix, which is constructed by using the relative importance of the alternatives with respect to each criterion. The vector $(a_{i1}, a_{i2}, \ldots, a_{in})$ represents the principal eigen-vector of an $n_x n$ reciprocal matrix which is determined by pair-wise comparisons of the impact of the $m$ alternatives on the ith criterion.

The global value of an alternative can be obtained by aggregating the contribution of each criterion to the overall goal through the summation of the product of the criteria weight and the performance of the alternative with respect to each criterion. The best alternative can be determined by comparing the aggregated value. The calculation of the aggregated score for each alternative can be obtained from the Eq. (1).

$$A_{AHPScore} = \max \sum_{j=1}^{n} a_{ij} w_j \quad for \quad i = 1,2,3,\ldots,m \tag{1}$$

Where $a_{ij}$ represents the relative value of alternative $A_i$ and $w_j$ denotes the respective weight when it is considered in terms of criteria $C_j$. Moreover, it is necessary to normalize the alternative rating and the weight to result in $\Sigma a_{ij} = 1$ and $\Sigma w_j = 1$. First step in AHP trend is to demonstrate the hierarchy structuring of real complex problem which the general objective is positioned at the highest level. The parameters and alternatives are shown in next level (Saaty 1992).

If the purpose of using the AHP technique is to select the suitable mining method for ore deposit, then one must positioned the suitable mining method at highest level and the most effective mining method parameters located in next level, finally the mining methods as an alternative will be located at the lowest level. In AHP technique the elements of each level is compared to its related element in upper level inform of pair-wise comparison method. The results of these comparisons are shown in matrix form Eq. (2).

$$A = \begin{bmatrix} a_1 & \cdots & a_{1n} \\ \vdots & \cdots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \qquad i,j = 1,2,...,n \tag{2}$$

Where: $a_{ij}$ is the priority of element $i$ compared to element $j$. It must be noted that, in pair comparison of criterion if the priority of element $i$ compared to element $j$ is equal to $w_{ij}$ then the priority of element $j$ compared to element $i$ is equal to $\frac{1}{w_{ij}}$, The priority of element compared to it is equal to one. The verbal terms of the Saaty's fundamental scale of 1–9 is used to assess the intensity of preference between two elements. The value of 1 indicates equal importance, 3 moderately more, 5 strongly more, 7 very strongly and 9 indicates extremely more importance. The values of 2, 4, 6 and 8 are allotted to indicate compromise values of importance (Saaty 1980). After calculation of alternative weight compared to criterion weight and criterion compared to objective, overall priority of each alternative can be calculated.

In order to investigate the competence of this technique for mining method selection, Reza-Abad bauxite ore deposit was chosen as practical application. The above mentioned Bauxite ore deposit is situated in east of Iran, Damghan. Physical parameters such as deposit geometry (general shape, ore thickness, dip and depth) grade distribution and rock mechanics characteristics and all other necessary data needed for evaluation all collected using field and laboratory tests, are given in Table 1. In this section, AHP with 18 sub-criteria was used to develop a suitable mining method. Three alternatives (Open pit, Shrinkage stoping and cut and fill stoping) were evaluated for exploitation of the Bauxite of RAD ore deposit.

This method contained the following three stages:

Stage 1 – Recognition of objective, criterions, sub-criterions and alternatives for creation of hierarchy structure. At this stage gathering all available information of ore deposit, the major factors effective on selection of mining methods were determined. Based upon study of this stage three criterion, 18 sub-criterions and three alternatives were recognized as an ingredient of hierarchy structure (Fig. 2).

TABLE 1

Characteristics of Reza-Abad Bauxite ore deposit

TABELA 1

Charakterystyka złoża rudy Reza-Abad

| Parameters | | Description |
|---|---|---|
| Ore zone | General deposit shape | platy |
| | Ore thickness | 1 meters |
| | Ore dip | 70 degree |
| | Grade distribution | Graditional |
| | Depth | 100 meters |
| | UCS | 1–5 MPa |
| | RQD | 20–40 |
| | RSS | 0.1 |
| | RMR | 42 |
| Hangwall | UCS | 50–100 MPa |
| | RQD | 40–70 |
| | RSS | 1.85 |
| | RMR | 65 |
| Footwall | UCS | 1–5 MPa |
| | RQD | 20–40 |
| | RSS | 0.1 |
| | RMR | 42 |

Where UCS: Uniaxial Compressive Strength, RQD: Rock Quality Design, RSS: Rock Substance Strength, RMR: Rock Mass Rating.

Stage 2 – In this stage based on experiences, engineering judgment and knowledge, pair-wise comparison of parameters was used to build up the matrix.

Stage 3 – The third stage of studies was the calculation of local and overall priorities of parameters and mining method with using Expert Choice (EC) software tool. At the end of process, as indicated in Table 2 cut & fill mining has highest priority and shrinkage has lowest priority for this deposit.

The power of the AHP approach lies in its ability to hierarchically structure a complex, multi-attribute problem into a comprehensive structure representing the decision maker's perception of the decision problem. One of the major advantages of AHP is that it calculates the inconsistency index as a ratio of the decision maker inconsistency and randomly generated index. This index is important for the decision maker to assure him that his judgments were consistent and that the final decision is made well. The inconsistency index should be lower than 0.1.

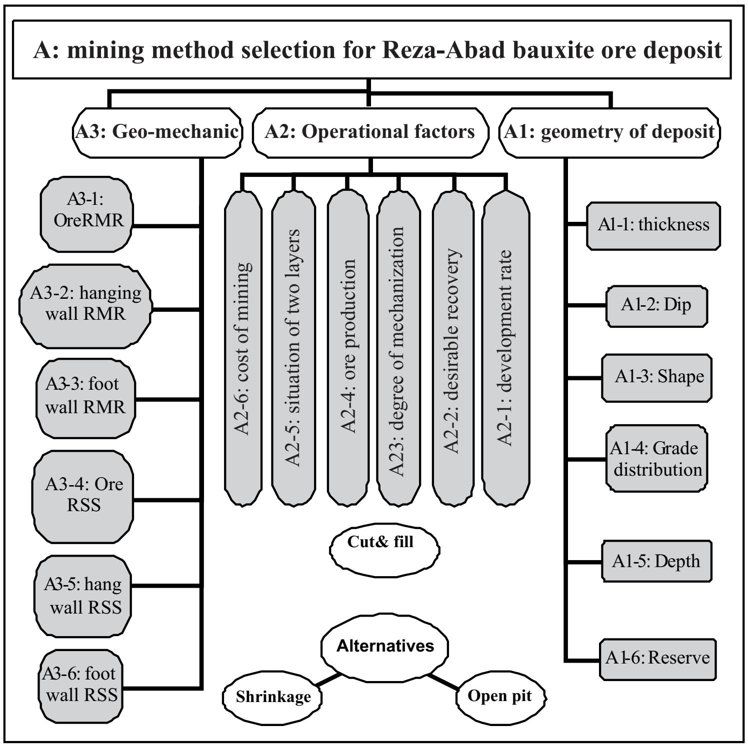


Fig. 2. Hierarchy structure of Reza-Abad bauxite ore deposit

Rys. 2. Struktura hierarchiczna dla złoża boksytów Reza-Abad

TABLE 2

AHP Results of mining method selection for Reza-Abad bauxite ore deposit

TABELA 2

Wyniki wyboru metody eksploatacji z zastosowaniem AHP dla złoża boksytów Reza-Abad

| Open pit | Shrinkage | Cut & fill | Weight | Parameter |
|---|---|---|---|---|
| 0.285 | 0.319 | 0.396 | 0.333 | Geometries |
| 0.273 | 0.245 | 0.482 | 0.500 | Operational |
| 0.373 | 0.248 | 0.379 | 0.167 | Geo-mechanic |
| 0.294 | 0.270 | 0.436 | - | Final score |

## 4. Technique for Order Preference by Similarity to Ideal Solution

TOPSIS was developed by Hwang and Yoon (1981). The basic concept of this method is that the selected alternative should have the shortest distance from the ideal solution in geometrical sense. The ideal solution is a solution that maximizes the benefit criteria/attributes and minimizes the cost criteria/attributes, whereas the negative ideal solution maximizes the cost criteria/attributes and minimizes the benefit criteria/attributes. The best alternative is the one, which is closest to the ideal solution and farthest from the negative ideal solution (Huang, Yoon 1981). Suppose a decision problem has $m$ alternatives $A_1,\dots,A_m$, and $n$ decision criteria/attributes $C_1,\dots,C_n$. Each alternative is evaluated with respect to the $m$ criteria/ /attributes. All the values/ratings assigned to the alternatives with respect to each criterion form a decision matrix denoted by $X = (x_{ij})_{nxm}$. Let $W = (w_1,\dots,w_n)$ be the relative weight vector about the criteria, satisfying $\sum_{i=1}^{n} w_i = 1$. Then the method can be summarized as.

A – Calculate the decision matrix ($D$) as Eq. (3).

$$D = \begin{bmatrix} X_{11} & \cdots & X_{1n} \\ \vdots & \cdots & \vdots \\ X_{m1} & \cdots & X_{mn} \end{bmatrix} \tag{3}$$

B – Calculate the normalized decision matrix or $R$ matrix. The normalized value is calculated by Eq. (4).

$$R = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \cdots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{bmatrix} \qquad r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \qquad i = 1,\dots,n, \quad j = 1,\dots,m \tag{4}$$

C – Calculate the criteria weighted matrix as Eq. (5).

$$W = \begin{bmatrix} w_1 & \cdots & 0 \\ \vdots & w_2 \cdots & \vdots \\ 0 & \cdots & w_n \end{bmatrix} \tag{5}$$

Where $w_j$ is the weight of the $j$ th attribute or criterion, and $\sum_{i=1}^{n} w_i = 1$.

D – Calculate the weighted normalized decision matrix. The weighted normalized value is calculated as Eq. (6).

$$v_{ij} = w_i r_{ij} = W \cdot R \qquad j = 1,\dots,m, \quad i = 1,\dots,n \tag{6}$$

E – Determine the positive ideal and negative ideal solution.

$$\begin{aligned} A^{+} &= \{v_1^{+},\dots,v_n^{+}\} = \{(\max_j v_{ij} \mid i \in I), (\min_j v_{ij} \mid i \in J)\} \\ A^{-} &= \{v_1^{-},\dots,v_n^{-}\} = \{(\min_j v_{ij} \mid i \in I), (\max_j v_{ij} \mid i \in J)\} \end{aligned} \tag{7}$$

Where is $I$ associated with benefit criteria, and $J$ is associated with cost criteria.

F – Calculate the separation measures, using the n-dimensional Euclidean distance. The separation of each alternative from the ideal solution and negative ideal solution is given as Eq. (8).

$$S_j^+ = \sqrt{\sum_{i=1}^{n} (V_{ij} - V_i^+)^2} \qquad S_j^- = \sqrt{\sum_{i=1}^{n} (V_{ij} - V_i^-)^2} \qquad j = 1, \ldots, m \tag{8}$$

G – Calculate the relative closeness ($RC$) to the ideal solution. The relative closeness of the alternative $A_j$ with respect to $A^+$ is defined as Eq.(9).

$$RC_j = \frac{S_j^-}{S_j^+ + S_j^-} \qquad j = 1, \ldots, m \quad \text{Since } S_j^- \geq 0 \text{ and } S_j^+ \geq 0 \text{ then clearly, } RC_j \in [0,1] \tag{9}$$

H – Rank the alternatives according to the relative closeness to the ideal solution. The bigger $RC_j$, is the better the alternative $A_j$. The best alternative is the one with the greatest relative closeness ($RC$) to the ideal solution.

In order to investigate the competence of this technique, Gol-E-Gohar (GEG) deposit No. 3 was chosen as practical illustration which is an iron ore deposit and located in 55 km of South-west of Kerman province of Iran. The above mentioned deposits are at the center of a triangle consisting of Kerman, Shiraz and Bandar-Abbas with height of 1750 m from sea level. The mentioned Iron ore district includes 6 anomalies. Recently, exploitation of deposit No. 3 has been considered. Deposit No. 3 with length of 2200 m in Northern-Southern line and with average width of 1800 m is located under a relatively flat field. Geometric speci- fications and some of Geo-mechanical specifications of Deposit No. 3 are represented in Table 3.

In order to select the method to extract this deposit, 11 methods are considered for comparison and competition. Examined extraction methods include: Open pit mining, Block caving, Sublevel stoping, Sublevel caving, Longwall, Room and pillar, Shrinkage, Cut and fill, Top slicing, Square-set, Stope and pillar. Parameters involved in this selection are according to Table 4 and 5.

In this decision making, attribute type or in the other word its effect on mine cost index decision making is entered as cost (negative effect on decision making) and for other parameters it is entered as profit. First, linguistic variable is transformed into a fuzzy triangular numbers. The linguistic variables divided to seven-levels, linguistic values "Very low", "Low", "More or Less (MoL) low", "Medium", "More or Less (MoL) high", "High" and "Very high". Based on these assumptions, a transformation table can be found as shown in Table 6. For example, the variable "Low" has its associated triangular fuzzy number with the minimum value of 0.00, the mode value of 0.10 and the maximum value of 0.3. The same definition is then applied to the other variables Very low, MoL low, Medium, MoL high, High and Very high (Samimi, Shahriar, Ataee, Dehghani 2008).

TABLE 3

Characteristics of GEG Iron ore deposit No. 3

TABELA 3

Charakterystyka złoża GEG Iron nr 3

| Parameters | | Description |
|---|---|---|
| Ore zone | Ore thickness | 15–130 meters (Average 40 meters) |
| | Ore dip | 20 degree |
| | Grade distribution | Gradational |
| | Depth | 95 ~ 600 meters |
| | UCS | 128.3 MPa |
| | RQD | 75% |
| | RSS | 8.9 |
| | RMR | Good (60–80) |
| | Joint condition | Filled with talk strength less than rock substance |
| Hanging wall | UCS | 46 MPa |
| | RQD | 38% |
| | RSS | 6 |
| | RMR | Good (60–80) |
| | Joint condition | Clean joint with a smooth surface |
| Foot wall | UCS | 100.5 MPa |
| | RQD | 15% |
| | RSS | 13 |
| | RMR | Good (60–80) |
| | Joint condition | Clean joint with a rough surface |

Where UCS: Uniaxial Compressive Strength, RQD: Rock Quality Design, RSS: Rock Substance Strength, RMR: Rock Mass Rating.

Then, in order to remove dimension, the decision matrix is normalized and calculated using weighted normalized ratings. The next action is to find the negative as well as the positive ideal solutions. After finding the ideal and negative ideal solutions, distance of each alternative is obtained in an n-dimensional space (n, is the number of criteria affecting decision making). Final scores of each parameter, is its relative closeness to the positive ideal solution. Table7 shows the points obtained by each extraction method in TOPSIS decision making, after the data processed. As you can see in the Table, Open pit mining with 75.71 points is the first and Square-set method with 30.86 scores is at the bottom of this ranking.

According this observations, advantages of the TOPSIS are addressed: a sound logic that represents the fundamental of human choice, a scalar value that account for both the best and worst alternatives simultaneously, a simple computation process that can be easily prog-

TABLE 4

Geometrical and geo-mechanical input data of GEG deposit No. 3

TABELA 4

Geometryczne i geomechaniczne parametry złoża GEG nr 3

| Suitability for Criteria | Deposit shape | Grade distribution | Ore dip | Ore thickness | Depth | Hanging wall RMR | Ore RMR | Hanging wall RSS |
|---|---|---|---|---|---|---|---|---|
| Block caving | Medium | Medium | Medium | Mol High | Mol High | Mol High | Low | High |
| Cut & fill | High | Mol High | Mol High | Mol low | Mol High | High | Mol High | Mol High |
| Longwall | High | Mol low | Low | Very low | Medium | High | Medium | Very High |
| Open pit | Medium | Mol High | Mol High | High | Low | High | Mol High | Mol High |
| Room& pillar | High | Medium | Low | Very low | Mol High | Mol High | Very High | Low |
| Shirinkage | High | Medium | Low | Very low | Mol High | Medium | Mol High | Low |
| Square-set | Mol low | Mol low | Mol High | Low | Mol low | Mol low | Low | High |
| Stope & pillar | High | Mol High | Medium | Mol High | Mol High | Mol High | Very High | Low |
| Sublevel caving | High | Medium | Mol low | High | Medium | Mol High | Mol low | High |
| Sublevel stoping | High | High | Mol low | High | High | Mol High | High | Low |
| Top slicing | Medium | Mol low | Medium | Medium | Mol low | Medium | Mol low | High |

TABLE 5

The rest of Geometrical and geo-mechanical input data of GEG deposit No. 3

TABELA 5

Pozostałe geometryczne i geomechaniczne parametry złoża GEG nr 3

| Suitability for Criteria | Ore RSS | Footwall RSS | Recovery | Skilled man power | Output per man shift | Hang wall RQD | Mining cost |
|---|---|---|---|---|---|---|---|
| Block caving | Medium | Medium | 90 | Very Low | 90 | Very High | (5,12.5,20) |
| Cut & fill | Mol Low | Medium | 100 | Medium | 30 | High | (15,32.5,50) |
| Longwall | Very High | Mol High | 95 | Medium | 40 | Very High | (5,15,25) |
| Open pit | Mol High | High | 100 | Very High | 90 | High | (3,11.5,20) |
| Room& pillar | Low | Medium | 60 | Mol High | 35 | Mol Low | (10,20,30) |
| Shirinkage | Mol Low | Mol High | 85 | Mol High | 12 | Very High | (15,27.5,40) |
| Square-set | Mol High | Low | 100 | Very Low | 8 | High | (30,77.5,125) |
| Stope & pillar | Low | Medium | 60 | Mol Low | 40 | Mol Low | (8,19,30) |
| Sublevel caving | Mol High | Medium | 85 | Mol Low | 35 | Very High | (12,26,40) |
| Sublevel stoping | Medium | Mol High | 85 | Mol High | 45 | Low | (12,23.5,35) |
| Top slicing | Medium | Mol Low | 95 | Medium | 10 | High | (20,42.5,65) |

rammed into a spreadsheet, and the performance measures of all alternatives on attributes can be visualized on a polyhedron, at least for any two dimensions. The major weaknesses of the TOPSIS are in not providing for weight elicitation, and consistency checking for judgments.

TABLE 6

Transformation for fuzzy triangular numbers

TABELA 6

Transformacje dla punktów rozmytych

| Rank | Membership function |
|---|---|
| Very low | (0.0, 0.0, 0.1) |
| Low | (0.0, 0.1, 0.3) |
| MoL low | (0.1, 0.3, 0.5) |
| Medium | (0.3, 0.5, 0.7) |
| MoL high | (0.5, 0.7, 1.0) |
| High | (0.7, 0.9, 1.0) |
| Very high | (0.9, 1.0, 1.0) |

TABLE 7

The scores obtained by each extraction method in TOPSIS

TABELA 7

Oceny uzyskane przez każdą z metod eksploatacji w TOPSIS

| Rank | Method | Score |
|---|---|---|
| 1 | Open pit | 75.71 |
| 2 | Sublevel stoping | 60.88 |
| 3 | Block caving | 58.36 |
| 4 | Long wall | 56.83 |
| 5 | Sublevel caving | 56.02 |
| 6 | Cut & fill | 55.43 |
| 7 | Stope & pillar | 52.44 |
| 8 | Room& pillar | 49.10 |
| 9 | Shrinkage | 46.85 |
| 10 | Top slicing | 45.40 |
| 11 | Square-set | 30.86 |

However, AHP's employment has been significantly restrained by the human capacity for information processing, and thus the number seven plus or minus two would be the upper limit in comparison. From this viewpoint, TOPSIS alleviates the requirement of paired comparisons and the capacity limitation might not significantly dominate the process. Hence, it would be suitable for cases with a large number of attributes and alternatives, and especially handy for objective or quantitative data given (Shih, Shyur, Lee 2007).

### 5. Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE)

The PROMETHEE uses the outranking principle to rank the alternatives, combined with the easy use and decreased complexity. It performs a pair-wise comparison of alternatives in order to rank them with respect to a number of criteria. According to Figure 3, Brans et al. have offered six generalized criteria functions for reference namely, usual criterion (I), quasi criterion (II), criterion with linear preference (III), level criterion (IV), criterion with linear preference and indifference area (V), and Gaussian criterion(VI) (Brans, Vincke, Marshal 1986).

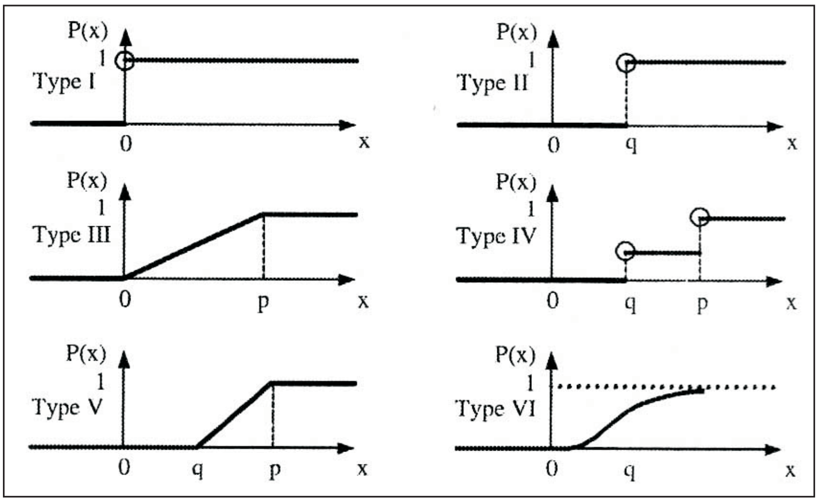


Fig. 3. Type of generalized criteria in PROMETHEE [37]

Rys. 3. Typy kryteriów ogólnych w PROMETHEE [37]

The method uses preference function $P_j(a,b)$ which is a function of the difference $d_j$ between two alternatives for any criterion $j$, i.e. $d_j = f(a,j) - f(b,j)$, where $f(a,j)$ and $f(b,j)$ are values of two alternatives $a$ and $b$ for criterion $j$.

The indifference and preference thresholds $q'$ and $P'$ are also defined depending upon the type of criterion function. Two alternatives are indifferent for criterion $j$ as long as $d_j$ does not exceed the indifference threshold $q'$. If $d_j$ becomes greater than $P'$, there is a strict preference. Multi-criteria preference index, $\pi(a,b)$ a weighted average of the preference functions $P_j(a,b)$ for all the criteria are defined as Eq. (10) (Pohrkar, Ramachandran 2004)):

$$\pi(b,a) = \frac{\sum_{j=1}^{J} w_j P_j(a,b)}{\sum_{j=1}^{J} w_j} \tag{10}$$

$$\Phi^{+}(a)=\sum_{A}\pi(a,b) \qquad \text{and} \qquad \Phi^{-}(a)=\sum_{A}\pi(a,b) \tag{11}$$

$$\Phi(a)=\Phi^{+}(a)+\Phi^{-}(a) \tag{12}$$

Where $w_j$, is the weight assigned to the criterion $j$; $\Phi^{+}(a)$ is the outranking index of $a$ in the alternative set $A$; $\Phi^{-}(a)$ is the outranked index of $a$ in the alternative set $A$; $\Phi(a)$ is the net ranking of $a$ in the alternative set $A$. The value having maximum $\Phi(a)$ is considered as the best one choice. $a$ Outranks $b$ if $\Phi(a)>\Phi(b)$; $a$ is indifferent to $b$ if $\Phi(a)>\Phi(b)$.

The following steps are required for the implementation of the method [39]:

(1) Alternatives are compared in pairs for each criterion. The preference is expressed by a number in the interval [0, 1] (0 for no preference or indifference to, 1 for strict preference). The function relating the difference in performance to preference is called the generalized criterion and it is determined by the decision maker.

(2) A multicriteria preference index is formed for each pair of alternatives as a weighted average of the corresponding preferences computed in step (1) for each criterion. The index $\pi(a,b)$ (in the interval [0, 1]) expresses the preference of alternative $a$ over $b$ considering all criteria. The weighting factors express the relative importance of each criterion and are chosen by the decision maker.

(3) Alternatives can be ranked according to:

— The sum of indices $\pi(a,i)$ indicating the preference of alternative $a$ over all the others. It is termed "leaving flow" $\Phi^{+}(a)$ and shows how "good" is alternative.

— The sum of indices $\pi(a,i)$ indicating the preference of all other alternatives compared to $a$. It is termed "entering flow" $\Phi^{-}(a)$ and shows how "inferior" is alternative $a$.

In order to investigate the competence of this method for mining method selection, Emarat Lead-Zinc ore deposit was chosen as a case study. This Lead-Zinc ore deposit is located in 25 km of South-west of Arak city in Central province of Iran. The above mentioned deposit is in a high land with height of 2000 meter from sea level, which is located in Sanandaj-Sirjan tectonic Zone. Footwall and hanging wall of this deposit is laminated marl calcite and shale respectively.

The main sulfur minerals of this deposit are Pyrite ($Fe_2S$), Sphalerite ($ZnS$) and Galena ($PbS$). The total reserve of Lead and Zinc ore is 1 105 234 tons. The thickness of above mentioned deposit is between 1.2–22 meters. Average weight of vertical thickness is 5.9 meters and overburden thickness and depth of deposit is 93 meters from ground surface. The average dip of this deposit is 65.6 degrees. Other geometric specifications and some of Geomechanical specifications of Emarat deposit have been summarized in Table 8. The generated parameters, which are needed for the method selection, are given briefly in this table together with related criterion.

In order to select the method to extract this deposit, 11 methods are considered for comparison and competition. Examined extraction methods include: Open pit mining, Block

TABLE 8

Specifications of Emarat Lead-Zinc ore deposit (Shariati 2006)

TABELA 8

Charakterystyka złoża cynku i ołowiu Emarat (Shariati 2006)

| Parameters | | Description |
|---|---|---|
| Ore zone | General deposit shape | Layer |
| | Ore thickness | 5.9 meters |
| | Ore dip | 65.6 degree |
| | Depth | 93 meters |
| | UCS | 154 MPa |
| | RQD | 65% |
| | RSS | 10.04 |
| | RMR | Good (60–80) |
| | Joint condition | Filled with talk strength less than rock substance |
| Hanging wall | UCS | 29.6 MPa |
| | RQD | 65% |
| | RSS | 1.9 |
| | RMR | Average (40–60) |
| | Joint condition | Clean joint with a smooth surface |
| Foot wall | UCS | 72.6 MPa |
| | RQD | 84% |
| | RSS | 4.7 |
| | RMR | Good (60–80) |
| | Joint condition | Clean joint with a rough surface |

Where UCS: Uniaxial Compressive Strength, RQD: Rock Quality Design, RSS: Rock Substance Strength, RMR: Rock Mass Rating.

caving, Sublevel stoping, Sublevel caving, Longwall, Room and pillar, Shrinkage, Cut and fill, Top slicing, Square-set, Stope and pillar.

These methods were defined as more applicable methods for these conditions at the end of the preliminary election considering the expert comments. Parameters involved in this selection include suitability of deposit shape, grade distribution, deposit dip, deposit thickness, deposit depth, hanging wall RMR, deposit RMR, Hanging wall Rock Substance strength (RSS=overburden pressure/UCS), deposit RSS, footwall RSS, extraction method recovery percentage, availability of skilled personnel, Production ability, hanging wall RQD.

The resulted weights of each parameter for alternatives in PROMETHEE method have been showed in Table 9. In Table 10, has been presented the points obtained by each extraction method in PROMETHEE method, after the data process.

TABLE 9

Weights of parameter in PROMETHEE method

TABELA 9

Wagi parametrów w metodzie PROMETHEE

| | Ore depth | Deposit shape | Ore thickness | Ore dip | Grade distribution | Ore RSS | Hanging wall RSS | Footwall RSS | Ore RMR | Hanging wall RMR | Footwall RMR |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Open pit | 0.10 | 0.06 | 0.09 | 0.04 | 0.14 | 0.12 | 0.11 | 0.23 | 0.14 | 0.12 | 0.23 |
| Block caving | 0.00 | 0.06 | 0.00 | 0.17 | 0.09 | 0.04 | 0.15 | 0.12 | 0.00 | 0.12 | 0.18 |
| Sublevel stoping | 0.05 | 0.13 | 0.05 | 0.17 | 0.19 | 0.17 | 0.00 | 0.18 | 0.18 | 0.00 | 0.12 |
| Sublevel caving | 0.00 | 0.13 | 0.00 | 0.17 | 0.09 | 0.12 | 0.15 | 0.12 | 0.04 | 0.17 | 0.18 |
| Long wall | 0.20 | 0.13 | 0.14 | 0.00 | 0.04 | 0.08 | 0.22 | 0.00 | 0.09 | 0.21 | 0.00 |
| Room & Pillar | 0.20 | 0.13 | 0.14 | 0.00 | 0.09 | 0.12 | 0.00 | 0.00 | 0.23 | 0.00 | 0.00 |
| Shrinkage | 0.05 | 0.13 | 0.19 | 0.17 | 0.09 | 0.12 | 0.00 | 0.18 | 0.14 | 0.00 | 0.12 |
| Cut & fill | 0.20 | 0.13 | 0.19 | 0.17 | 0.14 | 0.12 | 0.11 | 0.12 | 0.14 | 0.21 | 0.12 |
| Top slicing | 0.00 | 0.06 | 0.04 | 0.00 | 0.05 | 0.04 | 0.11 | 0.04 | 0.04 | 0.00 | 0.06 |
| Square-set | 0.20 | 0.03 | 0.14 | 0.09 | 0.05 | 0.04 | 0.15 | 0.00 | 0.00 | 0.17 | 0.00 |

TABLE 10

The scores obtained by each extraction method in PROMETHEE method

TABELA 10

Oceny uzyskane przez każdą z metod eksploatacji w metodzie PROMETHEE

| No. | Method | Score |
|---|---|---|
| 1 | Open pit | 0.19 |
| 2 | Block caving | –0.04 |
| 3 | Sublevel stoping | –0.24 |
| 4 | Sublevel caving | 0.03 |
| 5 | Long wall | –0.07 |
| 6 | Room & Pillar | –0.24 |
| 7 | Shrinkage | 0.11 |
| 8 | Cut & fill | 0.16 |
| 9 | Top slicing | 0.06 |
| 10 | Square-set | 0.03 |

At the end of the evaluation, Open pit mining method was found more suitable choice with (+0.19) points as an optimum mining method. The PROMETHEE method has some power in comparison with AHP method, such as: the PROMETHEE does not aggregate good scores on some criteria and bad scores on other criteria, it has less pair wise comparisons and it does not have the artificial limitation of the use of the 9-point scale for evaluation (Macharis, Springael, Berucker, Verbeke 2004).

## Conclusion

Mining method selection is one of the most important issues in mining engineering. From the viewpoint of system theory, the mining method selection problem is a multiple attribute decision making model with interactions between criteria. The application of the compensatory MADM techniques can be a useful tool for mining method selection problems where interactions between numerous aspects of selection are typically unavoidable. Existing compensatory MADM techniques can be classified into three broad categories: Value measurement models, Goal, aspiration and reference level models and Outranking models. The focus of this article is on AHP, TOPSIS and PROMETHEE as a sample of each category. AHP is one of the best known methods in first group and TOPSIS is one of the most important method that belong to the second group and finally PROMETHEE is the main family of method in Outranking group. With application of compensatory MADM techniques a strategy was offered to select the extraction method of mineral deposits. This strategy has advantages in comparison with previous numerical ranking (scoring) methods, including: Based on decision Theory, Possibility of sensitivity analysis in order to achieve more convenient results, infiniteness of the examined alternatives parameters affecting the selection of extraction method, and possibility of defining the problem according to local requirements, high speed in achieving the result and most important of all the possibility to consider the mutual effects of different parameters in selection process. MADM methods such as AHP, TOPSIS and PROMETHEE can be a good means to select the mining method for ore deposit in mining engineering. These methods proved to be a powerful and flexible tool to solve the mining method selection problems.

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## PRACTICAL APPLICATIONS FROM DECISION-MAKING TECHNIQUES FOR SELECTION OF SUITABLE MINING METHOD IN IRAN

K e y w o r d s

Decision theory, Multiple Attribute Decision Making, Mining method selection, Resources Management

A b s t r a c t

Mining method selection for an explored ore-body is the critical and problematic issues in mining engineering. Selection of an unsuitable method with regards to deposit characteristics may make exploitation of the ore-body troublesome and sometimes impossible or less economic. In the past, selection of extraction method was based primarily on operating experience at similar type mine and on methods already in use in the districts of the deposit. Recently application of decision theory has been paid attention for different selection problems. Decision-making methods are not using customarily in mining engineering but they are techniques can provide solutions to the problems involving conflicting and multiple criteria as mining method selection problems. This study presents of different decision making methods in complex environment of mining activities for optimal and efficient production. The focus of this article is on inspection of the suitable mining method selection and presentation of procedure, and is based on the decision theory. This paper is divided into two sections. The first section provides an overview of the mining method selection problems and decision making theory. The second section introduces an application of the Multiple Attribute Decision Making (MADM) for mining method selection accompanied by practical illustrations.

## PRAKTYCZNE ZASTOSOWANIA TECHNIK PODEJMOWANIA DECYZJI DO WYBORU ODPOWIEDNICH TECHNOLOGII EKSPLOATACJI W IRANIE

S ł o w a k l u c z o w e

Teoria podejmowania decyzji, wielokryterialna analiza decyzyjna, wybór metody eksploatacji, zarządzanie zasobami.

Streszczenie

Wybór metody eksploatacji dla udokumentowanego złoża rudy jest podstawowym i bardzo trudnym zagadnieniem w inżynierii górniczej. Wybór niewłaściwej technologii eksploatacji dla złoża o określonej charakterystyce może spowodować wiele kłopotów, a w rezultacie może doprowadzić do braku możliwości wybrania tego złoża lub uczynić eksploatację mniej opłacalną.

W przeszłości wybór metody eksploatacji wykonywany był na podstawie doświadczeń ruchowych w kopalniach podobnego typu, a opierano się na metodach już wykorzystywanych w innych częściach tego złoża. Ostatnio zwrócono uwagę na możliwość wykorzystania metod podejmowania decyzji do rozwiązywania problemów związanych z takim wyborem. Takie metody podejmowania decyzji nie są zwykle używane w górnictwie, ale są to techniki, które mogą dać rozwiązanie w zagadnieniach, w których występuje wiele wzajemnie sprzecznych kryteriów tak jak to ma miejsce w przypadku wyboru technologii eksploatacji. Artykuł prezentuje różne metody podejmowania decyzji dla osiągnięcia optymalnej i wydajnej produkcji w złożonych uwarunkowaniach związanych z działalnością górniczą. Celem tego artykułu jest, w oparciu o teorie podejmowania decyzji, wybór odpowiedniej metody eksploatacji oraz opis tej procedury. Artykuł podzielono na dwie części. Pierwsza część daje przegląd problemów związanych z wyborem metody eksploatacji oraz teorię podejmowania decyzji. Druga część omawia wielokryterialną analizę decyzyjną zastosowaną do wyboru metody eksploatacji wraz z przykładami.