Mining method selection by multiple criteria decision making tools

by M.R. Bitarafan and M. Ataei*

Synopsis

Mining method selection is the first and most important problem in mine design. In this selection some of the parameters such as geological and geotechnical properties, economic parameters and geographical factors are involved. The mining engineer must balance the input parameters and select the method that appears to be the most suitable; mining method selection is both an art and a science. Distinguishing all parameters that have an effect in mining method selection and in the determination of weighting factors of any parameter is a difficult task in an ordinary environment. This paper attempts to determine important parameters that impact on the mining method selection and demonstrates the calculation of the weighting factors for each selected parameter. This study has been directed to the research of a methodology for the selection of an optimal mining method. Different fuzzy methods are presented as an innovative tool for criteria aggregation in mining decision problems. Two methods of fuzzy multiple criteria decision making are used for selecting the optimal method with which to mine anomaly No. 3 of the Gol-Gohar iron mine. This paper finally presents a comparison of the selection methodologies and further discusses the most appropriate method investigated.

Introduction

Mining method selection is one of the most critical and problematic activities of mining engineering. The ultimate goals of mining method selection are to maximize company profit, maximize recovery of the mineral resources and provide a safe environment for the miners by selecting the method with the least problems among the feasible alternatives. Selection of an appropriate mining method is a complex task that requires consideration of many technical, economic, political, social, and historical factors. The appropriate mining method is the method which is technically feasible for the ore geometry and ground conditions, while also being a low-cost operation. This means that the best mining method is the one which presents the cheapest problem.

There is no single appropriate mining method for a deposit. Usually two or more feasible methods are possible. Each method entails some inherent problems. Consequently, the optimal method is one that offers the least problems.

The approach of adopting the same mining method as that of a neighbouring operation is not always appropriate. However, this does not mean that one cannot learn from comparing mining plans of existing operations in the district, or of similar deposits.

Each orebody is unique, with its own properties, and engineering judgement has a great effect on the decision in such the versatile job of mining. Therefore, it seems clear that only an experienced engineer who has improved his experience by working in several mines and gaining skills in different methods, can make a logical decision about mining method selection.

Although experience and engineering judgement still provide major input into the selection of a mining method, subtle differences in the characteristics of each deposit can usually be perceived only through a detailed analysis of the available data. It becomes the responsibility of the geologist and engineer to work together to ensure that all factors are considered in the mining method selection process.

Characteristics that have a major impact on the mining method selection include:

- Physical and mechanical characteristics of the deposit such as ground conditions of the ore zone, hangingwall, and footwall, ore thickness, general shape, dip, plunge, depth below the surface, grade distribution, quality of resource, etc. The basic components that define the ground conditions are: rock material shear strength, natural fractures and discontinuities shear strength, orientation, length, spacing and location of major geologic structures, *in situ* stress, hydrologic conditions, etc.

---

* *Department of Mining and Geophysics Engineering, Shahrood University of Technology, Shahrood, Iran*

© *The South African Institute of Mining and Metallurgy, 2004. SA ISSN 0038–223X/3.00 + 0.00. Paper received Nov. 2003; revised paper received Apr. 2004.*

- Economic factors such as: capital cost, operating cost, mineable ore tons, orebody grades and mineral value.
- Technical factors such as: mine recovery, flexibility of methods, machinery and mining rate.
- Productivity factors such as annual productivity, equipment, efficiency and environmental considerations.

Each of these criteria can become the principal determining factor in method selection, but the obvious predominance of one consideration should not preclude careful evaluation of all parameters.

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 match should be the one(s) considered technically feasible, and should then be evaluated economically.

Several methodologies have been developed in the past to evaluate suitable mining methods for an ore deposit, based on the physical and mechanical characteristics of the deposit such as shape, grade, and geomechanical properties of the rock. A group of mine scientists such as Boshkov and Wright (1973), Morrison (1976), Laubscher (1981) and Hartman (1987), suggested a series of approaches for suitable mining methods. These studies were neither enough nor complete, as it is not possible to design a methodology that will automatically choose a mining method for the orebody studied. The uses of numerical systems to evaluate the appropriateness of a mining method for a particular ore deposit have been in use for some time.

In 1981 Nicholas suggested for the first time a numerical approach for mining method selection. The Nicholas methodology follows a numerical approach to rate different mining methods based on the rankings of specific input parameters. A numerical rating for each mining method is arrived at by summing these rankings. The higher the rating, the more suitable the mining method. One of the problems of this approach was that all selection criteria had the same relevance. A recent modification involves the weighting of various categories, such as that of ore geometry, ore zone, hangingwall, and footwall (Nicholas 1992).

The wrong definition of some scores and the small domain between favourable and unfavourable scores prompted Miller, Pakalnis and Paulin (1995) to investigate the UBC approach. The UBC mining method selection is a modification of the Nicolas approach, which places more emphasis on stoping method, thus better representing typical Canadian mining design practices. Unfortunately, in the UBC approach, the importance of each selection criteria has not been considered. In addition, neither of these methods takes account of the uncertainty associated with boundary conditions of the categories used to describe input variables.

Fuzzy set theory

Acquiring the information necessary for mining method selection is an elaborate process, to say the least, and once obtained, data is likely to be ambiguous. In addition, decision makers must often apply rules of thumb or incorporate their personal intuition and judgement when deriving performance measures based on indefinite linguistic concepts, e.g. 'high', 'low', 'strong', 'weak', and 'stable'. Such terminology is common and is caused by imperfectly defined problem attributes.

Fuzzy sets have vague boundaries and are therefore well suited for representing linguistic terms such as 'very' or 'somewhat' or natural phenomena such as temperatures. Fuzzy set theory is used to describe fuzzy sets, and was developed as an alternative to ordinary (crisp) set theory. Fuzzy logic is used to derive the set membership function for a fuzzy set, which is used for fuzzy logic decision making. The problem of constructing meaningful and suitable membership functions involves a lot of additional research. A number of empirical ways to establish membership functions for fuzzy sets are known.

Fuzzy multiple attribute decision making

Multiple attribute decision making deals with the problem of choosing an alternative from a set of alternatives, which are characterized in terms of various attributes. Usually multiple attribute decision making involves the observance of a single goal. Two distinct aspects need to be considered. The first is the selection of an alternative on the basis of a set of scores determined from the levels of attributes of each alternative. The second is the classification of alternatives using a role model defined on the basis of similar-case outcomes. Multiple attribute decision making usually involves the use of a framework that applies subjective criteria. Goals require information about the preferences with respect to each attribute measure, as well as trade-off preferences among selected attributes. The assessment of these preferences is either provided directly by the decision maker or determined on the basis of past choices.

Further, the decision maker might express or define a ranking (weighting) for the criteria to reflect their importance. There are many forms for expressing the relative importance of criteria, but the most common are: utility preference functions; the analytical hierarchy processes; and fuzzy version of the classical linear weighted average. Notability for any fuzzy decision criteria could be fuzzy or crisp. The aim of multiple attribute decision making is to derive the best alternative as the one that shows the highest degree of satisfaction for all pre-elected attributes and predefined goals. In order to obtain the best alternative, a ranking process is required. If the rating for alternative A_k is crisp, there is no problem and the best alternative is the one with the highest support. When the rating is itself a fuzzy set, a more sophisticated ranking procedure is required.

The focus of this paper is on Yager's method, which is general enough to deal with both multiple objectives and multiple attribute problems. The Yager method (Yager, 1978) follows the max-min method of Bellman and Zadeh (1970), with the improvement of Saaty's method, which considers the use of a reciprocal matrix to express the pair-wise comparison criteria and the resulting eigenvector as subjective weights. The weighting procedure uses exponentials based on the definition of linguistic hedges, proposed by Zadeh (1973).

On describing multiple attribute decision making problems, only a single objective is considered, namely the selection of the best alternative from a set of alternatives. The decision method assumes the max-min principle approach. Formally, let A = $\{A_1, A_2,..., A_n\}$ be the set of alternatives, C = $\{C_1, C_2,..., C_m\}$ be the set of criteria, which can be given as fuzzy sets in the space of alternatives. Hence, the fuzzy set decision is the intersection of all criteria: $\mu_D(A) = \mathrm{Min}\{\mu_{C_1}(A_i), \mu_{C_2}(A_i), \ldots, \mu_{C_m}(A_i)\}$. For all $(A_i) \in A$, and the optimal decision is yielded by, $\mu_D(A^*) = \mathrm{Max}(\mu_D, (A_i))$, where A^* is the optimal decision.

A main difference in this approach is that the importance of criteria is represented as exponential scalars. This is based on the idea of linguistic hedges. The rationale behind using weights (or importance levels) as exponents is that the higher the importance of criteria, the larger should be the exponent, giving the minimum rule. Conversely, the less important a criterion, is the smaller its weight. This seems intuitive. Formally:

$$\mu_D(A_i) = Min\left\{\left(\mu_{C_1}(A_i)\right)^{a_1}, \left(\mu_{C_2}(A_i)\right)^{a_2}, \ldots, \left(\mu_{C_m}(A_i)\right)^{a_m}\right\} \qquad [1]$$

Consider the problem of selecting an alternative from a set of alternatives $\{A_1, A_2, A_3\}$ for which the set of criteria C_1, C_2, and C_3 is defined. The judgement scale used is as follows: 1 means equally important, 3 means weakly more important, 5 means strongly more important, 7 means demonstrably more important, and 9 means absolutely more important. The values between 2, 4, 6, and 8 indicate some compromised judgment (Saaty, 1990). Yager (1978) suggests the use of Saaty's method for pair-wise comparison of the criteria (attributes). A pair-wise comparison of criteria (attributes) could improve and facilitate the assessment of criteria importance. Saaty developed a procedure for obtaining a ratio scale for the elements compared. To obtain the importance, the decision maker is asked to judge the criteria in pair-wise comparisons and the values assigned are $w_{ij} = {}^1/w_{ij}$. Having obtained the judgements, an $m \times m$ matrix B is constructed so that $b_{ii} = 1$, and $b_{ij} = w_{ij}$ and $b_{ji} = {}^1/b_{ij}$.

Yager(1978) suggests that, with respect to a decision problem, the use of the resulting eigenvector expresses a decision maker's empirical estimate of the level of importance of alternatives for a given criterion (Basetin and Kesimal, 1999).

If C_2 and C_3 are three and two times as important as C_1, respectively, and C_2 is three times as important as C_3, the pair-wise comparison reciprocal matrix will be expressed as:

$$\begin{array}{c c} & \begin{array}{ccc} C_1 & C_2 & C_3 \end{array} \\ \begin{array}{c} C_1 \\ C_2 \\ C_3 \end{array} & \begin{bmatrix} 1 & \frac{1}{3} & \frac{1}{2} \\ 3 & 1 & 3 \\ 2 & \frac{1}{3} & 1 \end{bmatrix} \end{array}$$

Hence, the eigenvalues of the reciprocal matrix are $\lambda = [0 \; 3.053 \; 0]$ and, therefore, $\lambda_{\max} = 3.054$. The relative weights of the criteria are finally achieved in the eigenvector of the matrix, i.e. eigenvector = {0.157, 0.594, 0.249}, with $\lambda_{\max}$. The eigenvector reflects the weights associated with each attribute, feature and goal of a decision problem. Thus the exponential weightings are $\alpha_1 = 0.157$, $\alpha_2 = 0.594$, $\alpha_3 = 0.249$; the final decision expressed in a membership decision function, can be determined as follows: $\mu_D(\mathrm{A}) = \mathrm{Min}\{\mu_{C_1}{}^{0.157}, \mu_{C_2}{}^{0.594}, \mu_{C_3}{}^{0.249}\}$.

If the relative levels of importance of criteria for alternative A_1 are 0.75, 0.4 and 0.7, respectively, those for alternative A_2 are 0.8, 0.95 and 0.73, respectively, and those for alternative A_3 are 0.54, 0.32 and 0.4 respectively, then the applicable membership decision functions of alternatives A_1, A_2 and A_3, respectively, can be defined as follows:

$$\mu_D(\mathrm{A}_1) = \min\{(0.75)^{0.157}, (0.4)^{0.594}, (0.7)^{0.249}\} = 0.58$$
$$\mu_D(\mathrm{A}_2) = \min\{(0.8)^{0.157}, (0.95)^{0.594}, (0.73)^{0.249}\} = 0.92$$
$$\mu_D(\mathrm{A}_3) = \min\{(0.54)^{0.157}, (0.32)^{0.594}, (0.4)^{0.249}\} = 0.51$$

Consequently, the optimal solution, corresponding to the maximum membership level of 0.92, is given as

$$\mu_D(A^*) = \left(\frac{0.92}{A_2}\right).$$

Fuzzy dominance method

Hiple (1982) has proposed a flexible comparison technique known as the dominance matrix concept. Usually a dominance matrix is constructed for a typical element, d_{ij}, of the dominance matrix D, where d_{ij} is the number of the factor for which the value of alternative i dominates i.e. is greater than alternative j. A typical element d_{ij} of the dominance matrix is explicitly defined as follows:

$$d_{ij} = \sum_{k=1}^{n} \left\{\left[\mu_i(x_k) - \mu_j(x_k)\right] \geq 0\right\} \qquad [2]$$

Because the entries in the rating matrix are calculated using information which is often fuzzy or imprecise, a threshold level value can be chosen to represent the minimum amount by which one alternative must be greater than the other, for a given factor. In order for an alternative to be considered dominant for the factor the dimensionality of D is equal to the number of alternatives under consideration and dashes are entered for the diagonal elements since these elements have no meaning in the discrimination process (Hiple,1982 and 1983).

In the dominance matrix, the sum of the kth row indicates the number of times the kth alternative dominates all other alternatives. The sum of kth column represents the number of times the kth alternative is dominated by the others. Hence, the more preferable alternatives possess relatively high row sums and low column totals. These two attributes can be combined into a single measure by subtracting the column sum from the row sum for each alternative. The preferable alternative will have the highest difference.

Case study

The selection of a mining method has been considered for extracting the anomaly 3 at the Gol-Gohar iron mine. The Gol-Gohar iron mine is located 60 kilometres southwest of Sirjan city of Kerman province in Iran between 29° 3'' and 29° 7'' latitude and between 55° 15'' and 55° 24'' longitude. Kerman province is located in the southeast part of Iran. The Gol-Gohar iron mine contained six anomalies, Figure 1. Anomaly No. 3 is the biggest anomaly at this mine. On the basis of exploration work, the total ore reserves of anomaly No.3 are calculated as 616 million tons, with an average grade of 54.3 per cent Fe. Table I shows physical and mechanical characteristics of this deposit. Subsidence in this region is not prevalent and the mineral occurrence is uniform.

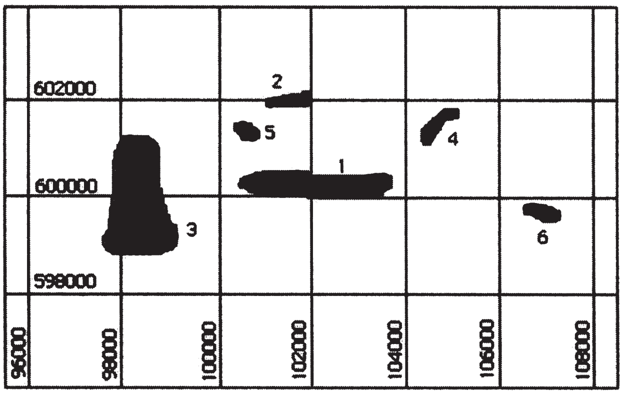


Figure 1—Six anomalies of Gol-Gohar mine

Table I

Technical parameters of anomaly No. 3 at Gol-Gohar mine (Ataei, 1998)

Parameter	Quality
Thickness	50–60 m
Dip	19–25 degree
Type	Massive
Grade distribution	Gradational
Depth	90–700 m
Rock substance strength of ore	7.7
Rock substance strength of hangingwall	8.4
Rock substance strength of footwall	12.8
RQD for walls and ore	25–35%
RMR for walls and ore	20–40

Table II

Criteria for mining method selection

Criterion	Operation
C_1	Thickness
C_2	Dip
C_3	Shape
C_4	Rock substance strength of ore
C_5	Rock substance strength of hangingwall
C_6	Rock substance strength of footwall
C_7	RMR of ore
C_8	RMR of hangingwall
C_9	RMR of footwall
C_{10}	Depth
C_{11}	Grade distribution
C_{12}	Subsidence
C_{13}	Technology
C_{14}	Recovery
C_{15}	Ore uniformity

In view of the technical parameters of anomaly No.3 of the Gol-Gohar mine (Table I), some mining methods are inappropriate. For example, the room and pillar and longwall methods, often used for low dip layers, or the shrinkage method often used for thicknesses greater than 30 m, cannot be used. The mining methods that were considered for extraction of this anomaly were as follows: cut and fill (CF), open pit (OP), square set (SQ), sublevel stoping (SLS), sublevel caving (SLC), top slicing (TC), and block caving (BC). The criteria that impact on the mining method selection, which were considered in this study, are summarized in Table II.

Fuzzy multiple attribute decision making

Let A = {*CF, OP, SQ, SLC, SLS, Ts, Bc*} be the set of possible mining alternatives and C = {C_1, C_2, ... , C_{15}} the set of selection criteria. A decision maker is asked to define the membership levels of each criterion after conferring with experts on this subject. Table III shows the membership levels of each criterion.

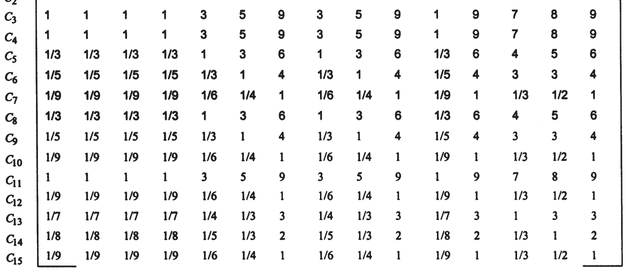
Table III

Membership level of each criterion

	CF	OP	SQ	SLC	SLS	TS	BC
C_1	0.1247	0.1395	0.0424	0.2130	0.2130	0.0941	0.1421
C_2	0.1908	0.1908	0.1908	0.0530	0.0530	0.1162	0.0872
C_3	0.0515	0.2402	0.0334	0.1526	0.1526	0.0515	0.2402
C_4	0.1511	0.1511	0.0389	0.0755	0.2784	0.0389	0.0755
C_5	0.1232	0.1232	0.0317	0.1232	0.2275	0.0317	0.0317
C_6	0.2016	0.2016	0.0355	0.0521	0.2016	0.0521	0.0521
C_7	0.1766	0.1766	0.0933	0.0933	0.0467	0.0933	0.1766
C_8	0.0243	0.0796	0.1404	0.1404	0.0796	0.0429	0.0796
C_9	0.2188	0.0929	0.0983	0.1450	0.0186	0.0186	0.0929
C_{10}	0.1952	0.0669	0.0631	0.1903	0.0676	0.0676	0.1952
C_{11}	0.2588	0.0117	0.0771	0.0771	0.0771	0.5040	0.1572
C_{12}	0.1428	0.2410	0.2410	0.0238	0.0785	0.0238	0.0238
C_{13}	0.1337	0.2431	0.1337	0.0366	0.0711	0.0215	0.0215
C_{14}	0.1298	0.0649	0.2528	0.0649	0.0649	0.1298	0.1298
C_{15}	0.1518	0.0467	0.1405	0.1357	0.1357	0.1357	0.1357

A 15 x 15 pair-wise comparison matrix (Figure 2) was constructed to express the decision makers' empirical estimate of the level of importance for each individual criterion. The maximum eigenvector was obtained from this matrix, using Matlab (version 6.0) software.

The respective weights of criteria were finally obtained from the eigenvector of the matrix i.e. eigenvector = {0.1410, 0.1410, 0.1410, 0.1410, 0.0673, 0.0365, 0.0117, 0.0673, 0.0365, 0.0117, 0.0239, 0.0165, 0.0117}. The eigenvector corresponds to the weights to be associated with the memberships of each criterion. The exponential weighting was consequently defined from each criterion as: α_1 = 0.1410, α_2 = 0.1410, α_3 = 0.1410, α_4 = 0.1410, α_5 = 0.0673,



	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}
C_1	1	1	1	1	3	5	9	3	5	9	1	9	7	8	9
C_2	1	1	1	1	3	5	9	3	5	9	1	9	7	8	9
C_3	1	1	1	1	3	5	9	3	5	9	1	9	7	8	9
C_4	1	1	1	1	3	5	9	3	5	9	1	9	7	8	9
C_5	1/3	1/3	1/3	1/3	1	3	6	1	3	6	1/3	6	4	5	6
C_6	1/5	1/5	1/5	1/5	1/3	1	4	1/3	1	4	1/5	4	3	3	4
C_7	1/9	1/9	1/9	1/9	1/6	1/4	1	1/6	1/4	1	1/9	1	1/3	1/2	1
C_8	1/3	1/3	1/3	1/3	1	3	6	1	3	6	1/3	6	4	5	6
C_9	1/5	1/5	1/5	1/5	1/3	1	4	1/3	1	4	1/5	4	3	3	4
C_{10}	1/9	1/9	1/9	1/9	1/6	1/4	1	1/6	1/4	1	1/9	1	1/3	1/2	1
C_{11}	1	1	1	1	3	5	9	3	5	9	1	9	7	8	9
C_{12}	1/9	1/9	1/9	1/9	1/6	1/4	1	1/6	1/4	1	1/9	1	1/3	1/2	1
C_{13}	1/7	1/7	1/7	1/7	1/4	1/3	3	1/4	1/3	3	1/7	3	1	3	3
C_{14}	1/8	1/8	1/8	1/8	1/5	1/3	2	1/5	1/3	2	1/8	2	1/3	1	2
C_{15}	1/9	1/9	1/9	1/9	1/6	1/4	1	1/6	1/4	1	1/9	1	1/3	1/2	1

Figure 2—Criterion comparisons

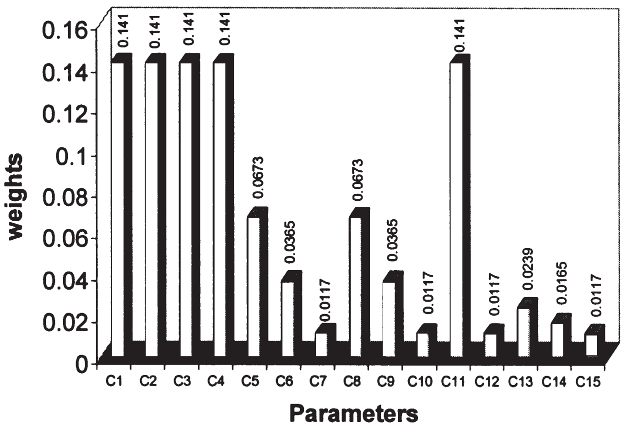


Figure 3—Comparison of criterions

$\alpha_6 = 0.0365$, $\alpha_7 = 0.0117$, $\alpha_8 = 0.0673$, $\alpha_9 = 0.0365$, $\alpha_{10} = 0.0117$, $\alpha_{11} = 0.1410$, $\alpha_{12} = 0.0117$, $\alpha_{13} = 0.0239$, $\alpha_{14} = 0.0165$, $\alpha_{15} = 0.0117$. Comparison of the criteria weighting is shown in Figure 3. The membership decision function according to Yager (1978) was determined for each alternative.

Using the max-min Bellman and Zadeh principle, the final set is determined as below

$$\mu_d(A) = \left\{ \frac{CF}{0.66}, \frac{OP}{0.534}, \frac{SQ}{0.62}, \frac{SS}{0.66}, \frac{SC}{0.66}, \frac{TS}{0.63}, \frac{BC}{0.695} \right\}$$

yielding the result:

$$\mu_d(A^*) = \max\{\mu_d(A_i)\} = 0.695$$

Which selects that block-caving method as preferable.

Fuzzy dominance method

In the fuzzy multiple attribute decision making section, fuzzy sets for each method (alternative) and their factors have been suggested. To use the dominance method and select an appropriate mining method for this anomaly, we need to use the data in Table IV. This matrix has 15 rows (effective criterions) and 7 columns (alternatives). In this matrix, weight of each criteria acts potentially.

Table IV

Membership decision function of each criterion by the Yager method

	CF	OP	SQ	SLC	SLS	TS	BC
C_1	0.75	0.76	0.64	0.80	0.80	0.72	0.76
C_2	0.79	0.79	0.79	0.66	0.66	0.74	0.98
C_3	0.66	0.82	0.62	0.77	0.77	0.66	0.82
C_4	0.77	0.77	0.63	0.70	0.84	0.63	0.70
C_5	0.77	0.87	0.80	0.87	0.90	0.80	0.80
C_6	0.94	0.94	0.89	0.90	0.94	0.90	0.90
C_7	0.95	0.98	0.97	0.97	0.96	0.97	0.98
C_8	0.78	0.84	0.88	0.88	0.84	0.81	0.84
C_9	0.95	0.92	0.92	0.93	0.86	0.86	0.92
C_{10}	0.98	0.97	0.97	0.98	0.97	0.97	0.98
C_{11}	0.83	0.54	0.70	0.70	0.70	0.91	0.77
C_{12}	0.98	0.98	0.98	0.96	0.97	0.96	0.96
C_{13}	0.95	0.97	0.95	0.98	0.94	0.91	0.91
C_{14}	0.97	0.96	0.98	0.96	0.96	0.97	0.97
C_{15}	0.98	0.96	0.98	0.98	0.98	0.98	0.98

Table V

Dominance matrix, mining method selection

	CF	OP	SQ	SLC	SLS	TS	BC	SUM
CF	*	5	7	7	7	8	6	**40**
OP	6	*	7	6	6	11	5	**41**
SQ	4	4	*	3	7	6	4	**28**
SLC	6	7	8	*	5	8	5	**39**
SLS	6	5	5	4	*	8	6	**34**
TS	4	3	4	3	4	*	1	**19**
BC	6	5	8	5	7	8	*	**39**
SUM	**32**	**29**	**39**	**28**	**36**	**49**	**27**	*

Following the procedure illustrated in the previous section, a dominance matrix can be created for the factors in Table IV. For this purpose, a 7x7 matrix is created by first associating each method with a corresponding row and column of the matrix: the cut and fill method corresponds to row 1 and column 1, open pit method to row and column 2, etc.

The element d_{12} of the dominance matrix is the number of performance factors for which cut and fill is greater than the open pit mining method. When the set of paired ratings {(0.75,0.76), (0.79,79), (0.66,0.82), (0.77,0.77), (0.77,0.87), (0.94,0.94), (0.95,0.98), (0.78,0.84), (0.95,0.92), (0.98,0.97), (0.83,0.54), (0.98,0.98), (0.95,0.97), (0.97, 0.96), (0.98,0.96)} is examined, it can be seen that cut and fill has a higher rating than open pit for five of the factors. Consequently, the value of d_{12} is 5. Similarly d_{21} possesses a magnitude of 6. The complete dominance matrix is displayed in Table V. In this table, in the last row and column, cumulative values for each row and column have been calculated.

In Table V the difference between column and row sums are 8,12,-11,11,-2,-30 and 12 for CF, OP, SQ, SLC, SLS, TS and BC, respectively. For this anomaly, clearly the alternative OP (open pit method) and BC (Block caving) are the most desirable alternatives for the given rating matrix. Therefore, this approach suggests the open pit mining and block caving method for anomaly No. 3 of Gol-Gohar anomalies.

Conclusion

Mining method selection is the fundamental decision made in a mine project, and a proper choice is critical as it affects almost all other major decisions. The selection of a suitable mining method for an ore deposit involves consideration of a diverse set of criteria. Several methods such as Nicolas, modified Nicolas and the UBC method have been developed in the past to evaluate suitable mining methods for an ore deposit. Unfortunately neither of these methods takes account of weighting factors for each criterion that impacts on mining method selection. This paper has discussed decision making in a fuzzy environment, i.e. uncertain data-linguistic variable for solving multiple attribute problems of mining method selection. The most important approaches and basic concepts were discussed. This paper presented a new approach for assigning criteria weighting.

For mining method selection in anomaly No. 3 of the Gol-Gohar iron mine, two methods of fuzzy decision making tools (fuzzy dominance and fuzzy multiple attribute decision making methods) were used. Weights for all alternatives were calculated. Results have showed that the block caving method would be preferable using fuzzy multiple attribute decision making, but open pit mining and block caving method would be preferable by the fuzzy dominance method. The fuzzy dominance method considers method selection criteria but the fuzzy multiple attribute decision making method considers method selection criteria and their weightings. Therefore, selection results derived from fuzzy multiple attribute decision making methods are comparatively more significant than those obtained using fuzzy dominance methods. Therefore, on the basis of the results presented, the most suitable mining method for extracting the mineralized anomaly at No. 3 Gol-Gohar iron mine is the block caving method.

References

ATAEI M. Study of anomaly No. 3 of Gol-Gohar iron mine of Iran, unpublished. 1998. pp. 1–54.

BASETIN A. and KESIMAL A. The study of a fuzzy set theory for the selection of an optimum coal transportation system from pit to the power plant, International Journal of Surface Mining, Reclamation and Environment vol. 13, pp. 97–101.

BELLMAN R.E. and ZADEH L. A. Decision Making In a Fuzzy Environment, *Management Science,* 17. 1970. pp. 141–164.

BOSHKOV, S.H. and WRIGHT, F.D. 'Basic and Parametric Criteria in the Selection, Design and Development of Underground Mining Systems,' *SME Mining Engineering Handbook,* A.B. Cummins and I.A. Given, (eds.), vol. 1, SME-AIME, New York. 1973. pp. 12.2–12.13.

HARTMAN, H.L. *Introductory Mining Engineering,* Wiley, New York. 1987. 633 pp.

HIPLE K. W. *Fuzzy set methodologies in multicriteria modeling, Fuzzy information and decision process,* M.M. Gupta and E. Sanchez (eds.), North-Holland Publishing Company. 1982. pp. 279–87.

HIPLE K. W. Fuzzy set techniques in decision making, *Resource Management and Optimization,* vol. 2, no. 3. 1983. pp.187–203.

LAUBSCHER, D.H. 'Selection of Mass Underground Mining Methods,' *Design and Operation of Caving and Sublevel Stoping Mines,* Chap. 3, D. Stewart, ed., SME-AIME, New York. 1981. pp. 23–38.

MILLER L., PAKALNIS R. and POULIN R. *UBC Mining method Selection, Mine planning and equipment selection* (MPES), Singhal (ed.), Balkama, Rotterdam. 1995.

MORRISON, R.G.K. *A Philosophy of Ground Control,* McGill University, Montreal, Canada. 1976. pp. 125–159.

NICHOLAS, D.E 'Method Selection—A Numerical Approach,' *Design and Operation of Caving and Sublevel Stoping Mines,* Chap. 4, D. Stewart, (ed.), SME-AIME, New York, 1981. pp. 39–53.

NICHOLAS D. E. Selection method, *SME Mining Engineering Handbook.* Howard L. Hartman (ed.), 2nd edition, Society for Mining Engineering, Metallurgy and Exploration, Inc. 1992. pp. 2090–2106.

Saaty T. L. *Decision-making for Leaders,* RWS Publication, USA. 1990.

YAGER R.R., Fuzzy Decision Making Including Unequal Objectives, *Fuzzy sets and systems,* vol. 1. 1978. pp. 87–95

ZADEH, L.A. Outline Of a New Approach to The Analysis of Complex Systems and Decision Process, *IEEE Trans,* vol. SMC 3, 1973. pp. 28–44.

◆

The South African Institute of Mining and Metallurgy
Founded in 1894

OBITUARY

		Date of Election	Date Deceased
E. Popplewell	Retired Fellow	24 March 1938	12 April 2004
D.A. Spalding	Associate	17 February 1984	9 September 2004