Mining method selection by AHP approach

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Synopsis

One of the most critical and complicated steps in mine design is a suitable mining method selection based upon geological, geotechnical, geographical and economical parameters. Since there are many factors involved in mining method selection, the decision-making process is very difficult. In this paper, the Analytical Hierarchy Process, with 13 criteria, is used to develop a suitable mining method for the Golbini No. 8 deposit in Jajarm (Iran). Six alternatives (conventional cut and fill, mechanized cut and fill, shrinkage stoping, sublevel stoping, bench mining, and stull stoping) are evaluated. The studies show that the suitable mining method for this deposit in the present situation is the conventional cut and fill method.

Introduction

Mining method selection is one of the most critical and problematic activities of mining engineering. The ultimate goals of mining method selection are maximizing company's profit and recovery of the mineral resources and providing a safe environment for the miners by selecting the suitable method with the fewest problems among the feasible alternatives. Selection of an appropriate mining method is a complex task that requires consideration of many technical, economical, political, social, and historical factors. The appropriate mining method is the method that is technically feasible for the ore geometry and ground conditions, while also being a low-cost operation.

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 the one that offers the fewest problems.

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

Each orebody is unique with its own properties, and engineering judgement has a greet effect on the decision in such versatile work as mining.

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 geologists and engineers to work together to ensure that all factors are considered in the mining method selection process. Figure 1 illustrates the flowchart of this study.

Analytical hierarchy process

Analytic hierarchy process (AHP) is a multi-attribute decision-making (MADM) technique, first developed in 1980 by Thomas L. Saaty. It is a tool to combine qualitative and quantitative factors in the selection of a process and is used for setting priorities in a complex, unanticipated, multi-criteria problematic situation. AHP provides a flexible and easy to understand way of analysing complicated problems. Therefore, AHP gives managers a rational basis for decision-making. It becomes quit popular in research because its utility outweighs other rating methods (Eddi and Hang, 2001). The AHP technique has been accepted by the international scientific community as a robust and flexible multi-criteria decision-making tool for dealing with complex decision problems (Elkarmi and Mustafa, 1993). The AHP model has found numerous and diverse applications and is practised successfully. This methodology has been applied to numerous decision problems

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 Paper received April 2007; revised paper received October 2008.

such as software selection, sourcing decisions, energy policy, supplier selection, project selection, measuring business performance, and evaluation of advanced manufacturing technology. The main advantage of AHP is its ability to handle complex and ill-structured problems, which cannot usually be handled by rigorous mathematical models. In addition to simplicity, ease of use, flexibility and intuitive appeal, the ability to mix qualitative and quantitative criteria in the same decision framework has led to AHP's power and popularity as a decision-making tool (Wedley, 1990).

Three features of AHP differentiate it from other decision-making approaches: (i) its ability to handle both tangible and intangible attributes, (ii) its ability to structure the problems in a hierarchical manner to gain insights into the decision-making process, and (iii) its ability to monitor the consistency with which a decision maker uses his/her judgement.

The three steps of AHP are decomposition, comparative judgement and synthesis. In the first step, a hierarchical structure is established to present the problem. The next step compares factors at the same level in pairs and measures their comparative contribution to the main objective. A comparison matrix was set up by comparing pairs of criteria or alternatives. A scale of values ranging from 1 (equally important) to 9 (extreme more important) was used to express evaluators' preferences. This pairwise comparison enables the decision maker to measure the contribution of each factor to the objective independently, thereby simplifying the decision-making process. The final step synthesizes priorities to calculate a composite weight for each alternative, based on preferences derived from the comparison matrix.

Basically, AHP has three underlying concepts: (i) structuring the complex decision problem as a hierarchy of goal, criteria, and alternatives, (ii) pairwise comparison of elements at each level of the hierarchy to each criterion on the preceding level, and (iii) vertically synthesizing the judgements over the different levels of the hierarchy (Saaty, 1980 and 1990).

The solution process consists of three stages, namely: (i) determination of the relative importance of the attributes; (ii) determination of the relative importance of each of the alternatives with respect to each attribute; (iii) overall priority weight determination of each of these alternatives.

AHP attempts to estimate the impact of each one of the alternatives on the overall objective of the hierarchy. An AHP can enable decision makers to represent the interaction of multiple factors in complex situations. The process requires the decision makers to develop a hierarchical structure for the factors which are explicit in the given problem and to provide judgements about the relative importance of each of these factors, and ultimately to specify a preference for each decision alternative with respect to each factor. The process provides a prioritized rank order indicating the overall degree of preference for each decision alternative.

The AHP approach has many different uses for solving problems; some of mining uses of this method are illustrated in Table I.

In this paper, the AHP approach with 13 criteria is used to develop a suitable mining method for the Golbini No.8 of Jajarm bauxite mine in Iran. A flowchart of the mining method selection by this method is shown in Figure 1.

Identification of main factors related to mining method selection

There are too many factors related to mining method selection such as geological and geotechnical properties, economic parameters, and geographical factors. It is very difficult to formulate definite criteria for the method selection that can satisfy all conditions of the mining simultaneously. 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.

Characteristics that have major impacts on mining method selection include:

➤ Physical and mechanical characteristics of the deposit such as ground conditions of the ore zone, hangingwall, footwall, ore thickness, general shape, dip, plunge, depth, 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.

Table I

Some applications of AHP in mining Engineering area

	Application areas	No. of attributes (No. sub-attributes)	No. of alternatives	Proposed by
1	Site selection for limestone quarry expansion	4 (13)	3	Kumar Dey, 2008
2	Optimum support design selection	8	9	Yavuz. *et al.* 2008
3	Environmental reclamation of an open pit mine	9	4	Bascetin. 2007
4	Underground mining method selection	6 (36)	5	Alpay and Yavuz. 2007
5	Rock mass classification on tunnel engineering	11	3	Chen and Liu. 2006
6	Alumina–cement plant location	5	5	Ataei, 2005
7	Equipment selection at open pit mine	4 (10)	4	Bascetin. 2004
8	Mining method selection	15	7	Bitarafan and Ataei 2004
9	Implementation of the AHP with VBA in ArcGIS	4	2	Marinoni. 2004
10	Drilling waste discharges	3 (5)	8	Sadiq. 2004
11	Optimal equipment selection in open pit mining	2 (4)	4	Bascetin. 2003
12	Selection of opencast mining equipment	7	5	Samanta *et al*. 2002
13	Evaluating the environmental impact of products	5	6	Hertwich. 1997

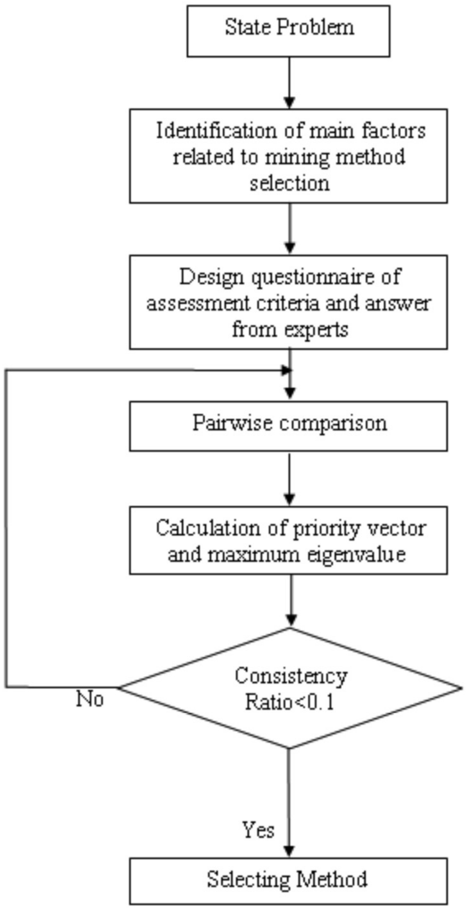

Figure 1—Flowchart of mining method selection by AHP approach

- Economic factors such as capital cost, operating cost, mineable ore tonnage, 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.

Questionnaire design and results of survey

As mentioned before, a large number of factors has an impact on mining method selection. This large number of criteria leads to (i) computational difficulty in making the pairwise comparisons in AHP, (ii) a time-consuming process and (iii) an unrealistic outcome. To overcome these problems, the main criteria or factors for method selection must be identified. For this reason a survey was conducted which 17 experts selected from different functional areas. They were all directly involved in the mine planning and design process. The objective of this survey was to assess the importance of the above-mentioned factors as criteria to be incorporated in the AHP model for the selection of a mining method.

For this purpose, a questionnaire with a five-point scale for each of the factors/criteria relating to the mining method selection was drawn up (Table II), and respondents were asked to rate a factor according to this scale. The mean value of each factor's/criteria was calculated as $\sum \frac{x_i f_i}{N}$,

where x_i is the number of respondents who picked a given rating associated with a particular factor, f_j is the corresponding of that rating and N is the total number of

Table II

Questionnaire with five-point scale to assess the importance of each factor

Criterion	Importance				
	1 None	2 Minor	3 Substantial	4 Fundamental	5 Highest
RMR of hangingwall					
RMR of footwall					
RMR ore					
Depth					
Deposit dip					
Deposit thickness					
Deposit shape					
Mechanizability					
Technology					
Ventilation					
Underground water					
Expert labour (miner)					
Subsidence					
Deposit size					
Investment					
Recovery					
Production					
Ore uniformity					
Cost					
Health/safety					
Environmental impacts					
Stability					
Selectivity					
Dilution					
Flexibility					
Ore grade					

respondents. The results of the survey are given in Table III. Half of the criteria that had the highest average and standard deviation less than 1.2 are considered to indicate important criteria for mining method selection. These criteria are considered the most important criteria for formulating the AHP model. Table IV and Figure 2 show the weight and normalized weight of these criteria. It was found that deposit thickness is most important (priority = 0.091) and it is followed by RMR of hangingwall and deposit dip (priority = 0.087).

Selection of mining method

For Golbini No.8 of the Jajarm mine conditions, six mining methods that were possible and appropriate to this mine, were considered. These methods are: conventional cut and fill (C&Fc), mechanized cut and fill (C&Fm), shrinkage stoping (SH), sub level stoping (SLS), bench mining (BM) and stull stoping (SS).

A weight was assigned to each method, based on the studied mine condition. This was done through a pairwise comparison. The pairwise comparisons were made with the aid of a scale. The scale used in AHP for preparing the pairwise comparison matrix is a discrete scale from 1 to 9 (Table V). The step was to find the relative priorities of alternatives implied by this comparison.

The hierarchy developed in this study consists of three levels. The top level represents the goal of selecting. The last level is represented by 13 criteria and the third level constitutes 6 alternatives (mining methods).

The use of this AHP model requires the owner's project team to discuss and determine the relative importance of each of the elements in the hierarchy. Each element in a level is compared pairwise with other elements at the same level, with respect to a criterion element at a higher level. The pairwise comparison is based on a scale of 1 to 9 as per the definition of weights given in Table V. A verbal scale is used

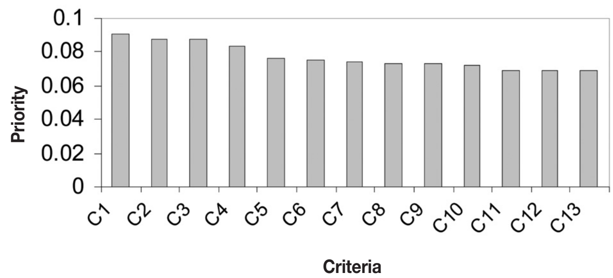

Figure 2—Comparison of attributes

Table V

Pairwise comparison scale

Comparison index	Score
Extremely preferred	1
Very strongly preferred	3
Strongly preferred	5
Moderately preferred	7
Equal	9
Intermediate values between the two adjacent judgments	2,4,6,8

Table III

The results of the survey

Criteria	Average	Standard deviation	Criteria	Average	Standard deviation
Deposit thickness	4.71	0.47	Technology	3.56	0.92
RMR of hangingwall	4.53	0.72	Depth	3.56	0.92
Deposit dip	4.53	0.62	Dilution	3.56	1.15
Deposit shape	4.47	0.74	Environmental impacts	3.50	1.21
Deposit size	4.13	1.26	Ventilation	3.44	1.34
RMR of ore	3.94	1.00	Selectivity	3.35	1.11
Ore grade	3.89	1.02	Health/safety	3.24	1.25
Investment	3.83	1.20	Mechanizability	3.22	1.22
Ore uniformity	3.83	0.99	Cost	3.20	1.21
Recovery	3.81	0.98	Flexibility	3.06	1.12
Production	3.78	1.17	Subsidence	3.00	1.03
Stability	3.73	1.28	Underground water	2.94	1.00
RMR of footwall	3.72	1.13	Expert labour (miner)	2.78	0.73

Table IV

Weight and normalized weight of the most important criteria

Criterion	Weight	Normalized weight	Criterion	Weight	Normalized weight
C1: Deposit thickness	4.71	0.091	C8: Recovery	3.81	0.073
C2: RMR of hangingwall	4.53	0.087	C9: Production	3.78	0.073
C3: Deposit dip	4.53	0.087	C10: RMR of footwall	3.72	0.072
C4: Deposit shape	4.47	0.084	C11: Technology	3.56	0.069
C5: RMR of ore	3.94	0.076	C12: Depth	3.56	0.069
C6: Ore grade	3.89	0.075	C13: Dilution	3.56	0.069
C7: Ore uniformity	3.83	0.074			

in AHP that enables the decision-maker to incorporate subjectivity, experience, and knowledge in an intuitive and natural way.

After comparison, matrices are created; relative weights are derived for the various elements. The relative weights of the elements of each level with respect to an element in the adjacent upper level are computed as the components of the normalized eigenvector associated with the largest eigenvalue of their comparison matrix. Composite weights are then determined by aggregating the weights through the hierarchy. This is done by following a path from the top of the hierarchy to each alternative at the lowest level, and multiplying the weights along each segment of the path. The outcome of this aggregation is a normalized vector of the overall weights of the options.

The next stage is calculation of the weight of criteria and alternatives. There are different ways to calculate of the weight such as least squares, logarithmic least squares, specific vector and estimating methods. The specific vector method is more watchful than other methods. In this method define W_i navigate to $A.W = \lambda.W$. λ is the specific quantity and W is the specific vector of pairwise matrix A. When the size of the matrix becomes larger, calculation of these quantities is really time-consuming.

After determining the weight of each criterion that obtain based upon questionnaire result, the comparison of each method based on a particular criterion is placed in the matrix. So 13 matrices are formed. Since the number of methods is six, the order of matrices is 6 × 6. Figures 3–15 present pairwise comparisons of the methods according to the each of the attributes.

AHP consistency is known as the consistency ratio (CR). This consistency ratio simply reflects the consistency of the pairwise judgements. For example, judgements should be transitive in the sense that if A is considered more important than B, and B more important than C, then A should be more important than C. If, however, the user rates A as important as C, the comparisons are inconsistent and the user should

	C&Fc	C&Fm	SH	SLS	SS	BM	Weight
C&Fc	1	3	3	3	9	9	0.4036
C&Fm	1/3	1	1	1	7	9	0.1792
SH	1/3	1	1	1	7	9	0.1792
SLS	1/3	1	1	1	7	9	0.1792
SS	1/9	1/7	1/7	1/7	1	3	0.0359
BM	1/9	1/9	1/9	1/9	1/3	1	0.023

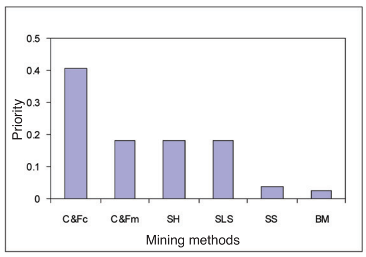

Figure 3—Comparison of methods with reference to thickness

	C&Fc	C&Fm	SH	SLS	SS	BM	Weight
C&Fc	1	1	3	7	7	3	0.3
C&Fm	1	1	3	7	7	3	0.3
SH	1/3	1/3	1	1	5	3	0.1
SLS	1/7	1/7	1	1	1	1/3	0.1
SS	1/7	1/7	1/5	1	1	1/3	0.1
BM	1/3	1/3	1/3	3	3	1	0.1

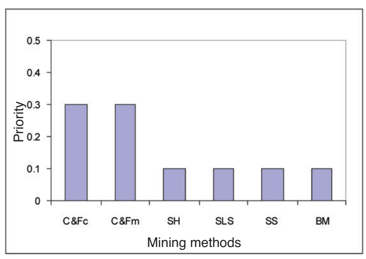

Figure 4—Comparison of methods with reference to RMR of hangingwall

	C&Fc	C&Fm	SH	SLS	SS	BM	Weight
C&Fc	1	1	1	1	5	1	0.1957
C&Fm	1	1	1	1	5	1	0.1957
SH	1	1	1	1	5	1	0.1957
SLS	1	1	1	1	5	1	0.1957
SS	1/5	1/5	1/5	1/5	1	1	0.0592
BM	1	1	1	1	1	1	0.1582

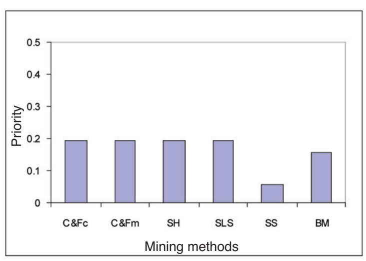

Figure 5—Comparison of methods with reference to deposit dip

	C&Fc	C&Fm	SH	SLS	SS	BM	Weight
C&Fc	1	1	3	3	3	3	0.25
C&Fm	1	1	3	3	3	3	0.2677
SH	1/3	1/3	1	1	1	1	0.2677
SLS	1/3	1/3	1	1	1	1	0.0541
SS	1/3	1/3	1	1	1	1	0.0487
BM	1/3	1/3	1	1	1	1	0.1117

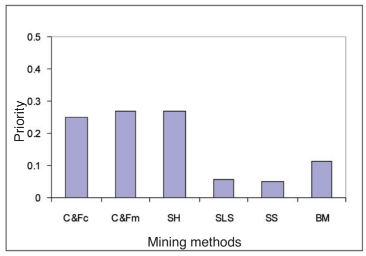

Figure 6—Comparison of methods with reference to deposit shape

	C&Fc	C&Fm	SH	SLS	SS	BM	Weight
C&Fc	1	1	3	3	9	7	0.0468
C&Fm	1	1	3	3	9	7	0.1585
SH	1/3	1/3	1	1	9	7	0.139
SLS	1/3	1/3	1	1	5	3	0.5506
SS	1/9	1/9	1/9	1/5	1	1/3	0.0298
BM	1/7	1/7	1/7	1/3	3	1	0.0753

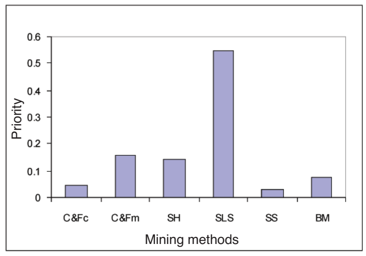

Figure 7—Comparison of methods with reference to RMR of ore

	C&Fc	C&Fm	SH	SLS	SS	BM	Weight
C&Fc	1	3	5	5	7	7	0.3263
C&Fm	1/3	1	3	3	5	5	0.3263
SH	1/5	1/3	1	3	3	3	0.1457
SLS	1/5	1/3	1	1	3	3	0.0581
SS	1/7	1/5	1/3	1/3	1	1	0.0399
BM	1/7	1/5	1/3	1/3	1	1	0.1038

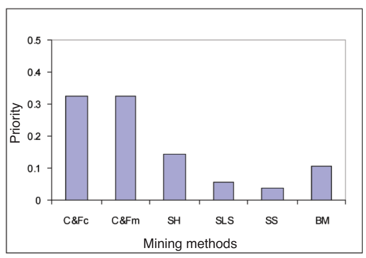

Figure 8—Comparison of methods with reference to ore grade

	C&Fc	C&Fm	SH	SLS	SS	BM	Weight
C&Fc	1	1	1	1	1	1	0.1667
C&Fm	1	1	1	1	1	1	0.1667
SH	1	1	1	1	1	1	0.1667
SLS	1	1	1	1	1	1	0.1667
SS	1	1	1	1	1	1	0.1667
BM	1	1	1	1	1	1	0.1667

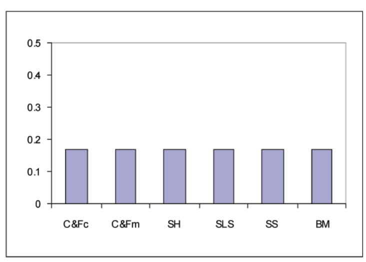

Figure 9—Comparison of methods with reference to ore uniformity

	C&Fc	C&Fm	SH	SLS	SS	BM	Weight
C&Fc	1	1	7	5	3	5	0.4493
C&Fm	1	1	7	5	3	5	0.2327
SH	1/7	1/7	1	1/3	1/5	1/3	0.1324
SLS	1/5	1/5	3	1	1/3	1	0.1011
SS	1/3	1/3	5	3	1	3	0.0422
BM	1/5	1/5	3	1	1/3	1	0.0422

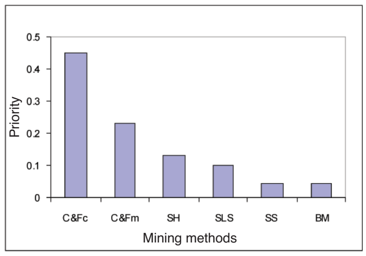

Figure 10—Comparison of methods with reference to recovery

	C&Fc	C&Fm	SH	SLS	SS	BM	Weight
C&Fc	1	1/5	1/3	1/9	3	1/3	0.3337
C&Fm	5	1	1	1/5	5	3	0.3337
SH	3	1	1	1/7	5	3	0.037
SLS	9	5	7	1	9	7	0.0695
SS	1/3	1/5	1/5	1/9	1	1/3	0.1566
BM	3	1/3	1/3	1/7	3	1	0.0695

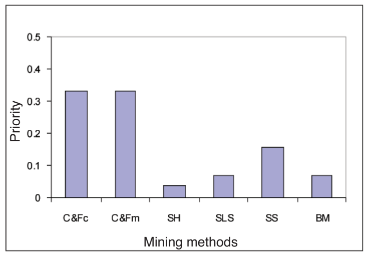

Figure 11—Comparison of methods with reference to production

	C&Fc	C&Fm	SH	SLS	SS	BM	Weight
C&Fc	1	1	1	1	1	1	0.1667
C&Fm	1	1	1	1	1	1	0.1667
SH	1	1	1	1	1	1	0.1667
SLS	1	1	1	1	1	1	0.1667
SS	1	1	1	1	1	1	0.1667
BM	1	1	1	1	1	1	0.1667

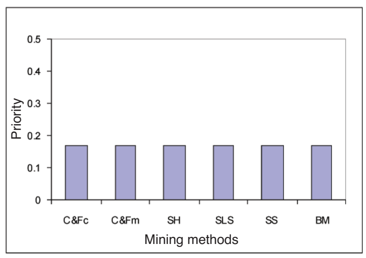

Figure 12—Comparison of methods with reference to RMR of footwall

	C&Fc	C&Fm	SH	SLS	SS	BM	Weight
C&Fc	1	1	1	3	5	3	0.3123
C&Fm	1	1	1	5	5	3	0.3123
SH	1	1	1	5	5	3	0.1551
SLS	1/3	1/5	1/5	1	1	1/3	0.1551
SS	1/5	1/5	1/5	1	1	1/3	0.0235
BM	1/3	1/3	1/3	3	3	1	0.0418

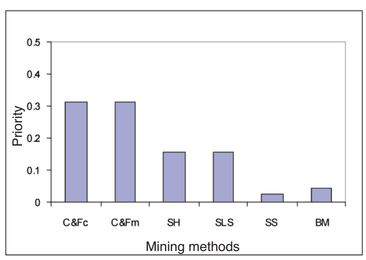

Figure 13—Comparison of methods with reference to technology

	C&Fc	C&Fm	SH	SLS	SS	BM	Weight
C&Fc	1	1	5	3	6	6	0.3468
C&Fm	1	1	3	3	6	6	0.3468
SH	1/5	1/3	1	1	2	2	0.0305
SLS	1/3	1/3	1	1	2	2	0.1715
SS	1/6	1/6	1/2	1/2	1	1	0.0305
BM	1/6	1/6	1/2	1/2	1	1	0.0739

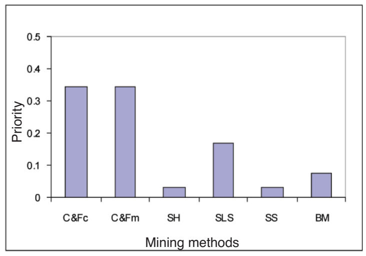

Figure 14—Comparison of methods with reference to depth

	C&Fc	C&Fm	SH	SLS	SS	BM	Weight
C&Fc	1	1	9	3	9	5	0.3582
C&Fm	1	1	9	3	9	5	0.3249
SH	1/9	1/9	1	1/7	1	1/3	0.1004
SLS	1/3	1/3	7	1	7	3	0.1083
SS	1/9	1/9	1	1/7	1	1/3	0.0541
BM	1/5	1/5	3	1/3	3	1	0.0541

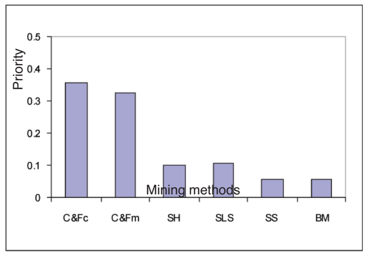

Figure 15—Comparison of methods with reference to dilution

revisit the assessment.

The consistency index (CI) of the pairwise comparison matrix is computed as:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad [1]$$

where λ_{max} maximum or principal eigenvalue and n is the size of the pairwise matrix. The random consistency index (RI) is given by:

$$RI = \frac{1.98\,(n-2)}{n} \quad [2]$$

The consistency ratio is given by

$$CR = \frac{CI}{RI} \quad [3]$$

The weight, λ_{max}, consistency index, random consistency

Table VI

Weight, , CI, RI and CR of matrices

Index / Factor	Weight	λ_{max}	CI	RI	CR
Goal	1	13	4.15E-11	1.6754	0
C1	0.091	6.31	0.062	1.32	0.047
C2	0.0875	6	0	1.32	0
C3	0.0875	6.3204	0.0641	1.32	0.0485
C4	0.0838	6.1051	0.021	1.32	0.0159
C5	0.0761	6.4155	0.0831	1.32	0.063
C6	0.0752	6.3954	0.0791	1.32	0.0599
C7	0.0741	6	0	1.32	0
C8	0.0737	6.4682	0.0936	1.32	0.0709
C9	0.073	6.2662	0.0532	1.32	0.0403
C10	0.0719	6	0	1.32	0
C11	0.0216	6.5934	0.1187	1.32	0.0899
C12	0.0622	6.1328	0.0664	1.32	0.0503
C13	0.0216	6.0293	0.0059	1.32	0.0044

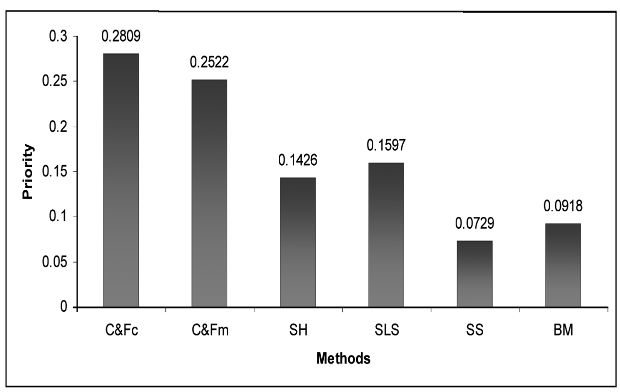

Figure 16—Overall rating

index and consistency ratio of criteria and goal are given in Table VI.

From Table VI it is found that the consistency index and consistency ratio for all parameters are less than 10%. This indicates that the committee is exhibiting coherent judgement in specifying the pairwise comparison of the criteria or alternatives.

Figure 16 presents the composite ranking of the methods in graphical form. It is seen from the figure that the method, conventional cut and fill, with a rating of 0.2886 is most preferred and is followed by mechanize cut and fill, sublevel stoping, shrinkage, stull stoping and bench mining methods.

Conclusion

Mining method selection involves the interaction of several subjective factors or criteria. Decisions are often complicated and many even embody contradiction. In this study, it was found that the Deposit thickness was the most important factor (priority = 0.091) for the selection of a suitable mining method, followed by the RMR of hangingwall and deposit dip (priority = 0.087). From six alternatives that were studied, conventional cut and fill was the most appropriate on consideration of all 13 factors in the mining method selection process. Unlike the traditional approach to mining method selection, AHP makes it is possible to select the best method in a more scientific manner that preserves integrity and objectivity. The model is transparent and easy to comprehend and apply by the decision maker. For selecting a mining method, the AHP model is unique in its identification of multiple attributes, minimal data requirement, and minimal time consumption.

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