Multicriteria choice of ore transport system for an underground mine: application of PROMETHEE methods

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Synopsis

The aim of this paper is to demonstrate the implementation of multicriteria analysis in selection of the most suitable underground ore transport system for a chromite mine in Turkey. The related problem includes five possible ore transport systems and six criteria to evaluate them. The adopted evaluation and ranking method for this study is PROMETHEE. PROMETHEE I revealed a partial order of alternatives where incomparability exists. PROMETHEE II gave the absolute ordering of alternatives. The results have shown that the PROMETHEE method can be successfully used in solving mining engineering problems.

Keywords: multi-objective, decision analysis, mining, ore transport system

Introduction

Dedeman-Krom is a small-scale underground mine situated in the middle of Anatolia, Kayseri, Turkey. This mine produces approximately 120 000 tons/year saleable high-grade chromite ore using partial mechanization. The extracted ore is transported to the surface from the 30 metre main levels in two stages. In the first stage the ore is carried by means of a mine car pushed manually up to the shaft. The second stage of transport uses a hoist that was initially designed for up to depths of 220 metres.

As the exploration works have discovered additional reserves to the depth of 500 metres, new ore transport systems have been found necessary because the present hoisting system will not be adequate for the in-depth reserve. Discussions have led to several alternative transport systems, which should be evaluated for the selection.

The decision on which alternative transport system is to be selected should be based not only on a one dimensional criterion of monetary cost but also on a multi-dimensional objective system called a 'benefit analysis'. This paper deals with the stages of a decision-making problem leading to selection of an alternative transport system for Dedeman underground chromite mine on the basis of a multicriteria choice, provided that further downward reserve increases have to be expected within the scope of future exploration activities.

The evaluation of alternatives is a decision-making problem and finding a solution to this type of problem is accomplished at stages that include[1,2,3,4,5,6]

1. *Analysis of the existing situation*: All of the related data are gathered at this stage.
2. *Description of problem and definition of criteria*: The problem is defined as a tension between the desired and current situation. In order to define the problem, the objectives and criteria to reach these objectives should be set.
3. *Determination and definition of alternatives*: On the basis of the problem description, alternatives for the system can be determined.
4. *Analysis of alternatives*: At this stage, the expected results of alternatives for each criterion are analysed.
5. *Evaluation of alternatives*: At this stage, the alternatives are compared to each other according to defined criteria.
6. *Decision-making*: The best of all alternatives is selected after the evaluation of alternatives.
7. *Development plans*: At this stage, basic and detailed engineering calculations are carried out for the selected alternative.
8. *Implementation plans*.

In this study, the first six steps have been investigated. Steps 7 and 8 are within the scope of operational planning.

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Main principles of a multi-dimensional objective problem

The most important part of the decision-making problem is to determine the relevant objectives and decision criteria derived from these objectives. After defining the criteria, possible alternatives are determined. After that, the alternatives are evaluated and ranked according to relevant criteria.

The evaluation of alternatives starts with the construction of matrix V consisting of v_{ij} elements, given as:

$$V = \begin{pmatrix} v_{11}v_{12}\ldots.v_{1j}\ldots.v_{1m} \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ v_{i1}v_{i2}\ldots\ldots v_{ij}\ldots\ldots v_{im} \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ v_{n1}v_{n2}\ldots\ldots v_{nj}\ldots\ldots v_{nm} \end{pmatrix}$$

where

v_{ij} , i=1……m; j=1…..n, indicates the performance value of alternative i according to criterion j. After constructing the value matrix V, the utility matrix K is constructed on the basis of matrix V. The matrix K is given as:

$$K = \begin{pmatrix} k_{11}k_{12}\ldots.k_{1j}\ldots.k_{1m} \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ k_{i1}k_{i2}\ldots\ldots k_{ij}\ldots\ldots k_{im} \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ k_{n1}k_{n2}\ldots\ldots k_{nj}\ldots\ldots k_{nm} \end{pmatrix}$$

where k_{ij} indicates the utility of alternative i according to criterion j and it is given as a function of v_{ij} as follows:.

$$k_{ij} = f\left(v_{ij}\right) \qquad [1]$$

It is a known fact that the relative importance of the different criteria differs from each other. In order to assess these differences, a quantitative weight for each criterion needs to be defined. Let g_j indicate the weight of criterion j. Then the weights of all criteria are given in matrix G as follows:

$$G = \begin{pmatrix} g_1 \\ \ldots \\ g_j \\ .. \\ g_m \end{pmatrix}$$

After defining the above matrixes, the rank of each alternative is determined by using the following equation[3]:

$$N = KxG \qquad [2]$$

In Equation [2], the vector N gives the total benefit of each alternative. In Equation [1], transformation of v_{ij} values into k_{ij} occurs on the basis of known judgment schemes. This and similar transformation are made on the basis of nominal, interval and cardinal ranking principles. The most widely used methods are nominal ranking methods, ordinal ranking methods (rank determination method, pair comparison method), interval ranking methods (direct ranking method, indirect ranking method, transformation of ordinal ranking into interval ranking, law of comparative judgment, law of categorical judgment) and ratio ranking methods (successive comparison method, scaling method on the basis of ratios, ranking method based on the direct ratio estimation).

In this study, the alternatives have been evaluated using a scaling method on the basis of ratios that is also called thePROMETHEE (Preference Ranking Ordering Methods Enrichment Evaluation) method because of its simplicity in conception and application compared to other methods[6–10]. The methodology of PROMETHEE is given below.

The utilization of PROMETHEE is a two-phase approach[6]. At the first phase, known as PROMETHEE I, partial preorder ranking of alternatives is obtained. At the second phase, known as PROMETHEE II, complete ranking of alternatives is obtained. The method requires defining the followings: preference function, generalized criterion function, and multicriteria preference index.

The preference function $P(x_i,x_k)$ represents the intensity of the preference of alternative x_i with regard to alternative x_k, $k\in(1,2,\ldots n)$ and such that;

$P(xi,xk)$ = 0 represents indifference or no preference of alternative xi over xk,

$P(x_i,x_k) \sim 0$ represents weak preference of x_i over x_k,

$P(x_i,x_k) \sim 1$ represents strong preference of x_i over x_k,

$P(x_i,x_k) = 1$ represents strict preference of x_i over x_k.

The evaluation of $P(x_i,x_k)$ is achieved through a generalized criterion function $H(d_{ik})$ which is directly related to the preference function P:

$$H\left(d_{ik}\right) = \begin{cases} P\left(x_i,x_k\right) & \text{if} \quad d_{ik} \geq 0 \\ P\left(x_k,x_i\right) & \text{if} \quad d_{ik} < 0 \end{cases} \qquad [3]$$

where

$$d_{ik} = v\left(x_i\right) - v\left(x_k\right)$$

$v\left(x_i\right)$….. value of alternative i,

There are six possible shapes of a generalized criterion function[6]. In this study, the usual criterion function is used and it is defined as following:

$$H\left(d_{ik}\right) = \begin{cases} 0 & \text{if} \quad d_{ik} = 0 \\ 1 & \text{if} \quad d_{ik} \neq 0 \end{cases} \qquad [4]$$

According to the usual criterion function, there is no difference between x_i and x_k if and only if $v(x_i) = v(x_k)$; as soon as the two evaluations are different, then there is a strict preference for the alternative having the greatest value.

After defining preference function and generalized criterion function, multicriteria preference index $\prod$ is defined as the weighted average of the preference functions $P(x_i,x_k)$:

$$\prod\left(x,x_k\right) = \frac{\sum_{j=1}^{k} w_j P\left(x_i,x_k\right)}{\sum_{j=1}^{k} w_j} \qquad [5]$$

$\prod(x_i,x_k)$ represents the intensity of preference of the decision maker of alternative x_i over alternative x_k. The value of preference index is between 0 and 1 and:

$\prod(x_i,x_k) \approx 0$ denotes a weak preference of x_i over alternative x_k for all the criteria,

$\prod(x_i,x_k) \approx 1$ denotes a strong preference of x_i over alternative x_k for all the criteria.

The preference index determines a valued outranking relation on the set of alternatives, and this relation can be represented as a valued outranking graph. Each alternative x_i is considered as a node in this graph. The leaving flow (positive preference flow) from node x_i measures its outranking character, and the entering flow (negative preference flow) measures its outranked character. The leaving flow is the sum of the values of the arcs leaving node x_i and defined by:

$$\Phi^+(x_i) = \sum_{k=1}^{m} \prod(x_i, x_k) \quad [6]$$

and entering flow is defined by:

$$\Phi^-(x_i) = \sum_{k=1}^{m} \prod(x_k, x_i) \quad [7]$$

Based on these negative and positive flows, the PROMETHEE I partial ranking of alternatives is obtained. The higher the leaving flow and the lower the entering flow, the better the action. The PROMETHEE II provides complete ranking of alternatives based on the net flow ($\Phi(x_i)$). The net flow is calculated by:

$$\Phi(x_i) = \Phi^+(x_i) - \Phi^-(x_i) \quad [8]$$

If $\Phi(x_i) > \Phi(x_k)$ then x_i outranks x_k, if $\Phi(x_i) = \Phi(x_k)$ then x_i indifferent from x_k,

Description of alternatives

There are many transportation alternatives for performing underground transportation activities. The number of alternatives grows on the basis of access position and this situation makes the problem more complex. However, with the help of restrictive criteria, a preselection of alternatives has been accomplished. This was a nominal evaluation and completed with the participation of a number of experts. After the evaluation of alternatives, the following alternatives were considered for further evaluation:

- *Deepening Existing Shaft* (DES): This alternative requires deepening the existing hoist shaft down to the –500 m level. Required development work includes sinking a 275 m shaft, driving a 2182 m haulage drift and a 900 m cross-cut.
- *Sinking Internal Shaft* (SIS): Alternative SIS requires deepening the existing hoist shaft to the 310 m level, then sinking an internal shaft from the 310 m level to the 500 m level. Required development work is sinking a 275 m shaft, driving of 1282 m haulage drift and a 900 m cross-cut
- *Sinking a New Shaft* (SNS): This alternative requires sinking a new hoist shaft. The new shaft will start at the surface and will be deepened down to the 500 m level. Required development work is sinking a shaft with a depth of 500 m, driving a 1917 m haulage drift and a 900 m cross-cut
- *Internal Ramp Haulage* (IRH): In this alternative, an internal ramp will be driven from the bottom of the existing shaft to the lower levels. The grade of the ramp will be between 10% and 15%. Extracted ore from the lower levels will be transported to the bottom of the existing shaft via underground trucks. Required development work is driving af 2443 m ramp and a 900 m cross-cut
- *External Ramp Haulage* (ERH): A ramp will be driven from the surface to the 250 m level. Then a ramp will be prepared as given in alternative IRH for lower levels. Extracted ore will be transported to the surface by means of underground trucks. Required development work is driving a 4210 m ramp and a 900 m cross-cut.

Criteria for selection of suitable alternatives

As a result of studying the existing situation and scenarios related to the future of the company, the following objectives of the transportation system were decided. The transportation system should:

- maintain the existing production level
- not result in capacity reduction for the reserve at the deeper levels
- be concordant with the mechanization in production activities
- require a minimum amount of development work
- not result in production stoppage during development
- reduce the number of required labour
- require a minimum amount of investment
- minimize ore transportation costs
- provide the necessary safety
- be easy to implement and operate
- not require additional roof support
- take into account the risk of reserve.

From the above objectives, which have been analysed and organized, the following evaluation criteria have been derived:

- Ore Production(OP)
- Total Investment Cost (IC)
- Unit Haulage cost (HC)
- Net Present Value(NPV)
- Ease of System application(ES)
- Risk of Reserve(RR).

There is a complementary relation between investment and unit haulage cost criteria and the net present value criterion. This complementary characteristic has been taken into account in evaluations.

Performance values of alternatives on the basis of criteria

The performance values of alternatives on the basis of criteria used in this study have been estimated and results are given in Table I. Details of the estimation can be found in[11]. Only a short explanation for each criterion is given as follows:

- *Ore Production* (OP): This is a maximization criterion and is expressed in annual production (ton/year). The annual ore production of each alternative will be different; therefore possible ore production figures are calculated on the basis of assumed technical factors and expressed in 10^3 ton.
- *Total Investment Cost* (IC): Total investment cost criterion is expressed in 1 000 US$. The necessary investment to build each alternative will be different due to the required development (shaft, drift, ramp, time period, etc.) work. The amount of development work and total cost of each alternative has been calculated. The management wants to minimize the total investment cost.

- *Unit Haulage Cost* (HC): The resulting haulage cost of each alternative is expressed in US$/ton and management wants it to be at the minimum level. The haulage cost consists of the owning and operating cost.
- *Net Present Value* (NPV): The main goal of any organization in the private mining sector is to maximize net present value of the reserve. The NPV of any mining operation depends on the life of a project. The shorter the project life is, the higher the NPV obtained. The development period of each alternative will be different; as a result, the life of project will be different. The resulting NPV of each alternative has been calculated on the basis of a 10% interest rate and results are expressed in 10^7 US$.
- *Ease of System* (ES): The ease of any alternative criteria is much more related to its implementation and additional utilization. Therefore this criterion is a subjective criterion. Rather than calculating the value of each alternative for this criterion, a grade between 0 and 10 is assigned to each alternative after elaborate discussion sessions with the engineering team of company. The higher the grade, the easier the system is, and the grade of each alternative is given in Table I.
- *Risk of Reserve* (RR): All mining investments are made on the basis of estimated mineable ore reserve. Fuzziness or inadequate information about the ore reserve creates an investment risk. Each alternative will provide some sort of additional information about the orebody during the development phase in order to guarantee the existence of the estimated mineable reserve. Some of the alternatives provide information earlier than others. The earlier the information is provided, the less the risk will be. Each alternative is assigned a grade between 0 and 10 after long discussion with the engineering team of the company and results are given in Table I.

Weight of criteria

Like most other multi-criteria decision methods, PROMETHEE methods also require definitions of quantitative weights for each criterion. It is often very difficult to obtain the values of weight, and the values given by a decision maker is not very precise. Several methods and techniques have been proposed to obtain weight estimates and to analyse the sensitivity of weights[10,13]. However, there is no generally accepted technique to obtain weights. Therefore, for the sake of this study, the management of different companies with similar situations and some experts have been questioned about the relative importance of criteria and they have been asked to provide a weight for each criterion. These weights have been checked using the following equation:

$$w_i = \left[2x\left(n+1-R_i\right)/\left(nx\left(n+1\right)\right)\right]$$

where,

n = number of criterion,

R_i = the nominal rank of evaluation,

w_i = weight of criterion i.

The average of the weights for each criterion given by the managers and experts is taken to be the weight of the considered criterion. The results and obtained weights are given in Table II.

Table I

Values of alternatives according to criteria

Criteria		Alternatives				
		DES	SIS	SNS	IRH	ERH
Ore production (OP)	Max	36	43	60	60	60
Investment cost (IC)	Min	3753	3360	4334	2787	3774
Haulage cost (HC)	Min	13	14.99	14.28	12.99	15.90
Net present value (NPV)	Max	12718	12368	10316	15242	13672
Ease of system (ES)	Max	3	1	3	7	5
Risk of reserve (RR)	Min	3	2	4	1	5

Implementation of PROMETHEE and results

Table III gives the evaluations of alternatives, the type of generalized criterion, and the relative weight of each criterion. Using the values given in Table III and Equations [3]–[7], values of the multi-criteria preference matrix are calculated and represented in Table IV.

The leaving flows are computed directly by adding the values of each row of the table, and the entering flows by adding the values of each column. The net flows are then easily obtained, using Equation [8], and results are given in Table V.

Table II

The weights given by the managers and averages

Decision Maker	Weights (%)					
	OP	IC	HC	NPV	ES	RR
DM1	30.0	25.0	20.0	15.0	5.0	5.0
DM2	19.0	19.3	28.0	19.5	4.7	9.5
DM3	20.0	25.0	15.0	15.0	12.0	13.0
DM4	22.8	19.2	28.5	12.2	9.1	8.2
DM5	21.0	16.6	21.0	15.0	10.6	15.8
DM6	16.7	22.2	22.2	16.7	11.1	11.1
DM7	16.7	33.3	25.0	8.3	16.7	–
DM8	18.2	36.4	13.6	9.1	18.2	4.5
Average	20.6	24.6	21.7	13.9	10.9	8.4

Table III

The multi-criteria data matrix

Criteria		DES	SIS	SNS	IRH	ERH	W	Criteria type
Ore production (OP)	Max	36	43	65	60	65	20.6	Usual
Investment cost (IC)	Min	3753	3360	4334	2787	3774	24.5	Usual
Haulage cost (HC)	Min	13	14.99	14.28	12.99	15.9	21.7	Usual
Net present (NPV)	Max	12718	12368	10316	15242	13672	13.9	Usual
Ease of system (ES)	Max	3	4	3	7	5	10.9	Usual
Risk of reserve (RR)	Min	3	2	4	1	5	8.4	Usual

After obtaining the leaving, entering, and net flow of each alternative, the partial preorder and complete ranking of alternatives are represented in Figure 1 and Figure 2 respectively.

Alternative IRH, as it was anticipated according to the evaluation matrix, is the preferable alternative, and alternative ERH follows as the second best alternative. According to the partial order of alternatives, alternatives SIS and ERH are incomparable. Alternative SIS presents low investment and operating cost. On the other hand, alternative ERH provides higher production and NPV. According to the complete ranking, the domination of alternative ERH against SIS is not so strong. Minor changes in weights might change the relative order of alternatives SIS and ERH. As expected in modern day mining, a higher degree of mechanization seems preferable.

Table IV

The multi-criteria preference matrix

Alternat.	DES	SIS	SNS	IRH	ERH	$\Phi^+(x_i)$
DES	0.000	0.355	0.684	0.000	0.546	1.585
SIS	0.645	0.000	0.467	0.000	0.546	1.658
SNS	0.206	0.533	0.000	0.206	0.301	1.244
IRH	1.000	1.000	0.795	0.000	0.793	3.588
ERH	0.455	0.455	0.493	0.207	0.000	1.609
$\Phi^-(x_i)$	2.305	2.342	2.439	0.412	2.185	

Table V

The net flows of each alternative

	DES	SIS	SNS	IRH	ERH
$\Phi(x_i)$	-0.720	-0.685	-1.195	3.176	-0.576

Conclusion

Dedeman chromite mine has expected a bottleneck concerning the ore transportation from the lower main levels in underground operations. The approaches to this problem have revealed several transport alternatives and several criteria to be considered in decision-making. The application of PROMETHEE multi-criteria decision-making methods to the selection of an underground ore transport system in this mine showed the following order in terms of diminishing preferences: alternative IRH (current shaft and a ramp), alternative ERH (ramp from surface), alternative SIS (internal shaft), alternative DES (deepening existing shaft), and alternative SNS (new hoist shaft). This complete order was obtained by means of PROMETHEE II. When the more refined techniques of PROMETHEE I were used, the existence of incomparable alternatives came to light to prove the importance of the weight of each alternative. Nevertheless, both methods used confirm the superiority of alternative IRH over other alternatives.

As a last word, this study has shown that multi-criteria decision methods can be successfully used in solving mining engineering problems.

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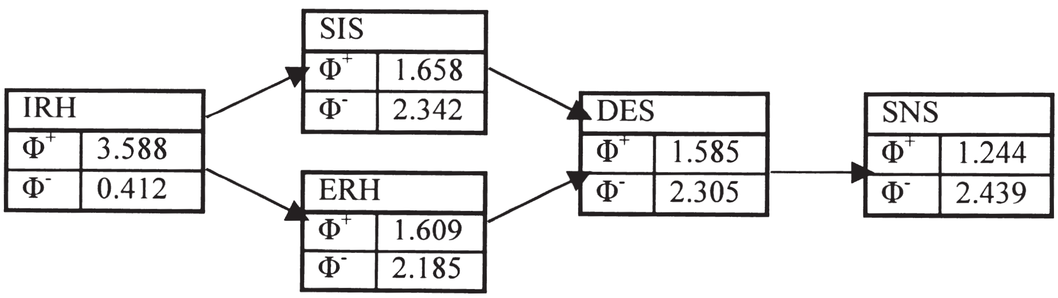

Figure 1—Partial ranking of alternatives according to PROMETHEE I

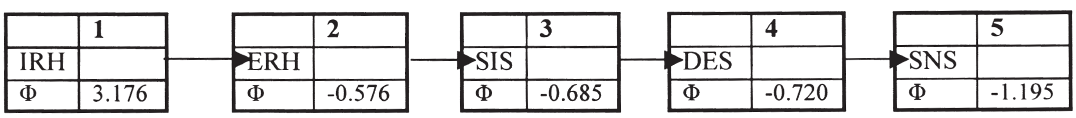

Figure 2—Complete ranking of alternatives according to PROMETHEE II

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