Expert Systems with Applications 38 (2011) 2550–2556

Contents lists available at ScienceDirect

Expert Systems with Applications

journal homepage: www.elsevier.com/locate/eswa

Deriving preference order of open pit mines equipment through MADM methods: Application of modified VIKOR method

Abbas Aghajani Bazzazi [a,*], Morteza Osanloo [a], Behrooz Karimi [b]

[a] Department of Mining and Metallurgical Engineering, Amirkabir University of Technology, Tehran, Iran
[b] Department of Industrial Engineering, Amirkabir University of Technology, Tehran, Iran

ARTICLE INFO

Keywords:
Multiple attribute decision making
VIKOR
Interval numbers
Mining equipment selection
Fuzzy data
Linguistic terms

ABSTRACT

In multiple attribute decision making (MADM) problem, a decision maker (DM) has to choose the best alternative that satisfies the evaluation criteria among a set of candidate solutions. It is generally hard to find an alternative that meets all the criteria simultaneously, so a good compromise solution is preferred. The VIKOR method was developed for multi-criteria optimization of complex systems. This method focuses on ranking and selecting from a set of alternatives in the presence of conflicting criteria. It introduces the multi-criteria ranking index based on the particular measure of “closeness” to the “ideal” solution. To deal with the uncertainty and vagueness from humans’ subjective perception and experience in decision process, this paper presents an evaluation model based on deterministic data, fuzzy numbers, interval numbers and linguistic terms. Combination of analytic hierarchy process (AHP) and entropy method was applied for attribute weighting in this proposed MADM method. To demonstrate the potential of the methodology, the proposed method is used for surface mine equipment selection problems.

1. Introduction

Multi-criteria optimization is the process of determining the best feasible solution according to the established criteria (representing different effects). Practical problems are often characterized by several non-commensurable and conflicting criteria and there may be no solution satisfying all criteria simultaneously. Thus, the solution is a set of non-inferior solutions, or a compromise solution according to the decision maker’s preferences.

The compromise solution was established by Zeleny (1982) for a problem with conflicting criteria and it can help the decision makers to reach a final solution. In classical MADM methods, the ratings and the weights of the criteria are known precisely, whereas in the real world, in an imprecise and uncertain environment, it is an unrealistic assumption that the knowledge and representation of a decision maker or expert are so precise. For example, human judgment including preferences is often vague and decision maker (DM) cannot estimate his preference with exact numerical values. In these situations, determining the exact value of the attributes is difficult or impossible. So, to describe and treat imprecise and uncertain elements present in a decision problem, fuzzy approaches and linguistic terms are frequently used.

In the works of linguistic terms decision making (Büyüközkan & Ruan, 2008), linguistic terms are assumed to be with known by fuzzy linguistic membership function. However, in reality to a decision maker it is not always easy to specify the membership function in an inexact environment. At least in some of the cases, the use of interval numbers may serve the purpose better. An interval number can be thought as an extension of the concept of a real number, however, in decision problems its use is not much attended as it merits (Moore, 1979).

Recently, some authors have extended TOPSIS and VIKOR method to solve decision making problems with interval data (Jahanshahloo, Hosseinzadeh, & Izadikhah, 2006; Sayadi, Heydari, & Shahanaghi, 2009; Ye & Li, 2009).

According to a comparative analysis of VIKOR and TOPSIS written by Opricovic and Tzeng (2004), VIKOR and TOPSIS methods use different aggregation functions and different normalization methods. TOPSIS method is based on the principle that the optimal point should have the shortest distance from the positive ideal solution (PIS) and the farthest from the negative ideal solution (NIS). Therefore, this method is suitable for cautious (risk avoider) decision maker(s), because the decision maker(s) might like to have a decision which not only makes as much profit as possible, but also avoids as much risk as possible. Besides, computing the optimal point in the VIKOR is based on the particular measure of “closeness” to the PIS. Therefore, it is suitable for those situations in which the decision maker wants to have maximum profit and the risk of the decisions is less important for him/her.

* Corresponding author. Tel.: +98 912 223 85 72; fax: +98 21 88306038.
E-mail addresses: abbas_aghajani_bazzazi@yahoo.com, a_aghajani@aut.ac.ir (A. Aghajani Bazzazi), morteza.osanloo@gmail.com (M. Osanloo), b.karimi@aut.ac.ir (B. Karimi).

0957-4174/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.eswa.2010.08.043

Therefore, in this paper, VIKOR method was extended to develop a methodology for solving MADM problems. What we basically suggest in this study is to extend the VIKOR method with four main types of information (deterministic data, fuzzy numbers, interval numbers and linguistic terms) in decision-making matrix for solving multiple attribute decision making problems. To validate the application of the model and to examine its effectiveness, the proposed extension methodology was used for deriving preference order of open pit mines equipment.

The selection of equipment for mining applications is not a well-defined process and because it involves the interaction of several subjective factors or criteria, decisions are often complicated and may even embody contradictions. Various types of cost model have been proposed for application to the selection of mining equipment. Expert system as decision aid in surface mine equipment selection was applied by Bandopadhyay and Venkatasubramanian (1987) and Denby and Schofield (1990). Hrebar (1990) and Sevim and Sharma (1991) used net present value analysis for selection of a dragline and surface transportation system. Use of a linear breakeven model has been proposed by Cebesory (1997). Models for equipment selection and evaluation described by Celebi (1998) were aimed at selection of the equipment fleet on the basis of minimizing the unit stripping cost and maximizing production. Hall and Daneshmand (2003) illustrated how reliability analysis can provide mine management with quantitative information of value for decision making about surface mining equipment. Analytical hierarchy process has proposed for application to selection of equipment by some researchers (Bascetin, 2004; Samanta, Sarkar, & Mukherjee, 2002). Application of AHP-TOPSIS (technique for order preference similarity to ideal solution) for loading–haulage equipment selection in open pit mines was used by Aghajani and Osanloo (2007). Application of fuzzy TOPSIS method for optimal open pit mining equipment selection has been illustrated by Aghajani Bazzazi, Osanloo, and Karimi (2009). Most of these decision-making tools either rely on objective input data, with little or no subjective judgment, or spotlight on a single parameter. Also, because of incomplete or non-obtainable information, the data (attributes) are often not so deterministic; there for they usually are fuzzy-imprecise and application of fuzzy logic and interval terms for surface mine equipment selection are exigent.

2. VIKOR method

Decision-making problem is the process of finding the best option from all of the feasible alternatives. In almost all such problems, the multiplicity of criteria for judging the alternatives is pervasive. For many such problems, the DM wants to solve a multiple attribute decision making (MADM) problem (Hwang & Yoon, 1981). A MADM problem can be concisely expressed in matrix format as:

$$D = \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccccc} C_1 & C_2 & C_3 & \cdots & C_n \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & x_{13} & \cdots & x_{1n} \\ x_{21} & x_{22} & x_{23} & \cdots & x_{2n} \\ x_{31} & x_{32} & x_{33} & \cdots & x_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m22} & x_{m3} & \cdots & x_{mn} \end{bmatrix} \end{array} \quad (1)$$

where $A_1, A_2, \ldots, A_m$ are possible alternatives among which decision makers have to choose, $C_1, C_2, \ldots, C_n$ are criteria with which alternative performance are measured, x_{ij} is the rating of alternative A_i with respect to criterion C_j.

The foundation for compromise solution was established by Yu (1973) and Zeleny (1982) and later advocated by Opricovic and Tzeng (2002, 2003, 2004, 2007), Tzeng, Tsaur, Laiw, and Opricovic (2002), Tzeng, Teng, Chen, and Opricovic (2002) Tzeng, Lin, and Opricovic (2005). The compromise solution is a feasible solution that is the closest to the ideal solution, and a compromise means an agreement established by mutual concession. The compromise solution method, also known as the VIKOR (VIšekriterijumsko KOmpromisno Rangiranje) method was introduced as one applicable technique to implement within MADM. The multiple attribute merit for compromise ranking was developed from the Lp-metric used in the compromise programming method (Zeleny, 1982)

$$L_{p,i} = \left\{ \sum_{j=1}^{M} (W_j[(m_{ij})_{\max} - (m_{ij})]/[(m_{ij})_{\max} - (m_{ij})_{\min}])^p \right\}^{1/p}$$
$$1 \leqslant p \leqslant \infty; \quad i = 1, 2, \ldots, N \quad (2)$$

where W_j is attribute weight and m_{ij} is normalized decision matrix elements.

Within the VIKOR method $L_{1,i}$ (as S_i in Eq. (3)) and $L_{\infty,i}$ (as R_i in Eq. (4)) are used to formulate the ranking measure. The main procedure of the VIKOR method is described below:

Step 1: The first step is to determine the objective, and to identify the pertinent evaluation attributes. Also determine the best, i.e., $\left(f_j^+\right)$, and the worst, i.e., $\left(f_j^-\right)$, values of all attributes.

Step 2: Calculate the values of S_i and R_i:

$$S_i = \sum_{j=1}^{M} w_j \left(\left[f_j^+ - (f_{ij}) \right] \Big/ \left[f_j^+ - f_j^- \right] \right) \quad (3)$$

$$R_i = \max_j \text{ of } \left(w_j \left[f_j^+ - (f_{ij}) \right] \Big/ \left[f_j^+ - f_j^- \right] \right) \Big| \, j = 1, 2, \ldots, M \} \quad (4)$$

Step 3: Calculate the values of Q_i:

$$Q_i = v((S_i - S^-)/(S^+ - S^-)) + (1 - v)((R_i - R^-)/(R^+ - R^-)) \quad (5)$$

where S^+ is the maximum value of S_i, and S^- the minimum value of S_i; R^+ is the maximum value of R_i, and R^- is the minimum value of R_i. v is introduced as weight of the strategy of 'the majority of attributes'. Usually, the value of v is taken as 0.5. However, v can take any value from 0 to 1.

Step 4: Arrange the alternatives in the descending order, according to the values of Q_i. Similarly, arrange the alternatives according to the values of S_i and R_i separately. Thus, three ranking lists can be obtained. The compromise ranking list for a given v is obtained by ranking with Q_i measures. The best alternative, ranked by Q_i, is the one with the minimum value of Q_i.

Step 5: For given attribute weights, propose a compromise solution, alternative A_1, which is the best ranked by the measure Q, if the following two conditions are satisfied (Tzeng et al., 2005):

Condition 1: 'Acceptable advantage' $Q(A_2) - Q(A_1) \geqslant (1/(N-1))$. A_2 is the second-best alternative in the ranking by Q.

Condition 2: 'Acceptable stability in decision making'. Alternative A_1 must also be the best ranked by S and/or R. This compromise solution is stable within a decision-making process, which could be: 'voting by majority rule' (when $v > 0.5$ is needed) or 'by consensus' (when $v \approx 0.5$) or 'with veto' (when $v < 0.5$).

If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of:

- Alternatives A_1 and A_2 if only condition 2 is not satisfied.
- Alternatives $A_1, A_2, \ldots, A_m$ if condition 1 is not satisfied; A_m is determined by the relation $Q(A_m) - Q(A_l) < (1/(N-1))$ for maximum M (the positions of these alternatives are "in closeness").

VIKOR is a helpful tool in MADM, particularly in a situation where the decision maker is not able, or does not know how to express preference at the beginning of system design. The obtained compromise solution could be accepted by the decision makers because it provides a maximum 'group utility' (represented by S^-) of the 'majority' and a minimum of individual regret (represented by R^-) of the 'opponent' (Opricovic & Tzeng, 2002, 2003, 2004, 2007).

3. The proposed modified VIKOR method

Although the VIKOR method has numerous advantages, the performance rating is quantified as crisp values. However, under many circumstances, crisp data are inadequate to model real-life situations. Since human judgments including preferences are often vague, it is difficult to rate them as exact numerical values. In addition, in case of conflicting situations or criteria, a DM must also consider imprecise or ambiguous data, which is very usual in this type of decision problems. A more realistic approach may be to use linguistic assessments, fuzzy numbers and interval data instead of crisp values, that is, to suppose that the ratings of the criteria in the problem are assessed by means of these types of data.

Combination of analytic hierarchy process and entropy method is another important concern in this study. Since entropy weighting passively determines attribute weights without a decision-makers conscious intention, the opportunity to learn during the attribute weighting process is eliminated which in turn may reduce both DM understanding and expectance. Thus, neither entropy weighting nor the AHP are entirely adequate for determining attribute importance weights in complex real-world situations. However, the innovative integration of the AHP and entropy weighting could potentially serve as a critical component of a comprehensive solution for classifying and prioritizing product requirements.

3.1. Entropy weighting

Shannon and Weaver (1947) proposed the entropy concept and this concept have been highlighted by Zeleny (1982) for deciding the objective weights of attributes. Entropy weighting is a MADM method used to determine the importance weights of decision attributes by directly relating a criterion's importance weighting relative to the information transmitted by that criterion. For example, given a MADM decision matrix with column vector $x_j = (x_{1j}, x_{2j}, \ldots, x_{mj})$ that shows the contrast of all alternatives with respect to jth attribute, an attribute has little importance when all alternatives have similar outcomes for that attribute. Moreover, if all alternatives are the same in relation to a specific attribute then that attribute should be eliminated because it transmits no information about decision-makers preferences. In contrast, the attribute that transmits the most information should have the greatest importance weighting. Mathematically this means that the projected outcomes of attribute j, P_{ij}, are defined as:

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{6}$$

The entropy E_j of the set of projected outcomes of attribute j is:

$$E_j = -\left(\frac{1}{\ln m}\right) \sum_{i=1}^{m} P_{ij} \ln P_{ij} \tag{7}$$

where m is the number of alternatives and guarantees that E_j lies between zero and one. The degree of diversification d_j of the information provided by outcomes of attribute j can be defined as $d_j = 1 - E_j$. Hence, the entropy weighting of an attribute is calculated as follows:

$$W_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{8}$$

In situations where a decision-maker has an a priori λ_j subjective weighting for an attribute, a compromise weighting, w_j^0, that takes into account both a decision maker's subjective preference and the objective entropy weighting of the attribute is calculated as follows:

$$w_j^0 = \frac{\lambda_j w_j}{\sum_{j=1}^{n} \lambda_j w_j} \tag{9}$$

Whereas entropy weighting provides a dynamic and objective assessment of a decision maker's attribute preference relative to the decision-making process, a priori weighting methods such as the AHP deceptively determine attribute importance statically and independently of the decision-making process.

3.2. Analytic hierarchy process

This method has been developed by Saaty (1990) and Saaty and Vargas (1994). The AHP structures the decision problem in levels which correspond to one understands of the situation: goals, criteria, sub-criteria and alternatives. By breaking the problem into levels, the DM can focus on smaller sets of decisions. In AHP technique the elements of each level compared to its related element in upper level inform by pair-wise comparison method.

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 $1/w_{ij}$. The priority of element compared to it is equal to one.

AHP method is applied in this research for criteria weighting. So, at first, set up n criteria in the rows and columns of $n \times n$ matrix. Then, Perform pair-wise comparisons of all the criteria according to the goal. The fundamental scale used for this purpose is shown in Table 1. For a matrix of order n, $((n) \times (n-1)/2)$ comparisons are required. Use average over normalized columns to estimate the Eigen values of the matrix. The redundancy of the pair-wise comparisons (Table 1) makes the AHP much less sensitive to judgment errors; it also lets one measure judgment errors by calculating the consistency index of the comparison matrix, and then calculating the consistency ratio.

3.3. Standardization methods

There are many standardization methods to deal with decision-making matrix. Generally there are two kinds of attributes, the benefit type and the cost type. The higher the benefit type value is, the better it will be. While for the cost type, it is the opposite. According to the need of this paper, we introduce standardization methods for deterministic number, interval number, triangle fuzzy number and linguistic terms below for standardization matrix M.

3.3.1. Deterministic numbers standardization

Here, mark that precision number is k_{ij}, after being standardized, is m_{ij} for benefit index, method as follows:

Table 1
Scale for pair-wise comparisons.

Numerical assessment	Linguistic meaning
1	Equal important
3	Moderately more important
5	Strongly more important
7	Very strongly important
9	Extremely more important
2, 4, 6, 8	Intermediate values of importance

$$m_{ij} = \frac{k_{ij}}{\max_j k_{ij}} \quad (1 \leqslant i \leqslant m, 1 \leqslant j \leqslant n) \tag{10}$$

For cost index method as follows:

$$m_{ij} = \frac{\min_j k_{ij}}{k_{ij}} \quad (1 \leqslant i \leqslant m, 1 \leqslant j \leqslant n) \tag{11}$$

3.3.2. Interval numbers standardization

Here, mark the interval number is $\left[k_{ij}^L, k_{ij}^U\right]$, after being standardized, is $\left[m_{ij}^L, m_{ij}^U\right]$. For the benefit type, the normalized formulas for the interval value are described as follows (Zhu, Liu, & Fang, 2007):

$$\left.\begin{aligned} m_{ij}^L &= \frac{k_{ij}^L}{\max_j k_{ij}^U} \\ m_{ij}^U &= \frac{k_{ij}^U}{\max_j k_{ij}^U} \end{aligned}\right. \quad 1 \leqslant i \leqslant m,\ j \in I_1 \tag{12}$$

Similarly, the formulas for interval value of the cost type are described as follows:

$$\left.\begin{aligned} m_{ij}^L &= \frac{\min_j k_{ij}^L}{k_{ij}^U} \\ m_{ij}^U &= \frac{\min_j k_{ij}^L}{k_{ij}^L} \end{aligned}\right. \quad 1 \leqslant i \leqslant m,\ j \in I_2 \tag{13}$$

The normalization method mentioned above is to preserve the characteristic that the ranges of normalized interval values belong to [0,1].

3.3.3. Triangle fuzzy number standardization

Here, mark the triangle fuzzy number is $\left(k_{ij}^L, k_{ij}^M, k_{ij}^U\right)$, after being standardized, is $\left(m_{ij}^L, m_{ij}^M, m_{ij}^U\right)$. For benefit index, method as follows:

$$\left.\begin{aligned} m_{ij}^L &= \frac{k_{ij}^L}{\max_j k_{ij}^U} \\ m_{ij}^M &= \frac{k_{ij}^M}{\max_j k_{ij}^U} \\ m_{ij}^U &= \frac{k_{ij}^U}{\max_j k_{ij}^U} \end{aligned}\right. \quad 1 \leqslant i \leqslant m,\ j \in I_1 \tag{14}$$

For cost index, method as follows:

$$\left.\begin{aligned} m_{ij}^L &= \frac{\min_j k_{ij}^L}{k_{ij}^U} \\ m_{ij}^M &= \frac{\min_j k_{ij}^L}{k_{ij}^M} \\ m_{ij}^U &= \frac{\min_j k_{ij}^L}{k_{ij}^L} \end{aligned}\right. \quad 1 \leqslant i \leqslant m,\ j \in I_2 \tag{15}$$

3.3.4. Linguistic terms standardization

Linguistic terms can be transferred into triangle fuzzy number, then use the Eqs. (14) and (15) to standardize. Table 2 is applied for transformation linguistic terms to triangular fuzzy numbers.

3.4. Steps of modified VIKOR method

– **Step 1:** According to standardization matrix M, draw out the positive ideal value and negative ideal value of each index, $f^+ = \{f_1^+, f_2^+, f_3^+, \ldots, f_n^+\}$ is positive ideal solution and $f^- = \{f_1^-, f_2^-, f_3^-, \ldots, f_n^-\}$ is negative ideal solution. Positive ideal solution:

$$f_j^+ = \max_j m_{ij} \tag{16}$$

And negative ideal solution:

$$f_j^- = \min_j m_{ij} \tag{17}$$

Table 2
Transformation linguistic terms to triangular fuzzy numbers.

Linguistic terms	Triangle fuzzy numbers
The best	(0.8,0.9,1)
Better	(0.7,0.8,0.9)
Very good	(0.6,0.7,0.8)
Good	(0.5,0.6,0.7)
Normal	(0.4,0.5,0.6)
Bad	(0.3,0.4,0.5)
Very bad	(0.2,0.3,0.4)
Worse	(0.1,0.2,0.3)
The worst	(0,0.1,0.2)

It deserves mentioned that in positive ideal solution and negative solution all type of data (crisp, interval, triangle fuzzy number and linguistic terms) may be taken into account. First introduce four definitions for calculating distance, minimum and maximum value of triangle fuzzy number and interval numbers.

Definition 1. Let $M = (a,b,c)$ be triangular fuzzy number, then the mean and standard deviation of M calculated as:

$$\begin{aligned} \overline{X}(M) &= \frac{1}{3}(a+b+c) \\ \sigma(M) &= \frac{1}{18}(a^2+b^2+c^2-ab-ac-bc) \end{aligned} \tag{18}$$

Suppose that (a_1,a_2,a_3) and (b_1,b_2,b_3) are two triangular fuzzy numbers that we want to choose maximum between them. These two fuzzy numbers have two statuses: (1) the maximum is the one that has upper mean value. (2) If mean value of two fuzzy numbers is equal then the maximum is the one that has lower standard deviation.

Definition 2. Suppose that $[a^L,a^U]$ and $[b^L,b^U]$, are two interval numbers that we want to choose minimum interval number between them. These two interval numbers can have four statuses:

(1) If these interval numbers have no intersection, the minimum interval number is the one that has lower values. In other words: If $a_U \leqslant b_L$ then, we choose $[a_L,a_U]$ as minimum interval number.
(2) If two interval numbers are the same, both of them have the same priority for us.
(3) In situations that $a_L \leqslant b_L < b_U \leqslant a_U$, if $(b_L - a_L) \geqslant (a_U - b_U)$ then $[a_L,a_U]$ is minimum interval number, else $[b_L,b_U]$ is minimum interval number.
(4) In situations that $a_L < b_L < a_U < b_U$, if $(b_L - a_L) \geqslant (b_U - a_U)$ then $[a_L,a_U]$ is minimum interval number, else $[b_L,b_U]$ is minimum interval number.

Definition 3. Distance between $[a^L,a^U]$ and $[b^L,b^U]$ is:

$$D(a,b) = \frac{\sqrt{2}}{2}\sqrt{(a^L-b^L)^2+(a^U-b^U)^2} \tag{19}$$

Definition 4. Distance between (a_1,a_2,a_3) and (b_1,b_2,b_3) is:

$$D(\tilde{a},\tilde{b}) = \frac{\sqrt{3}}{3}\sqrt{(a_1-b_1)^2+(a_2-b_2)^2+(a_3-b_3)^2} \tag{20}$$

– **Step 2:** In this step, compute S_i, R_i and Q_i:

$$S_i = \sum_{j=1}^{n} w_j \frac{D\left(F_j^+, m_{ij}\right)}{D\left(F_j^+, F_j^-\right)} \tag{21}$$

$$R_i = \max_j \left[w_j \frac{D\left(F_j^+, m_{ij}\right)}{D\left(F_j^+, F_j^-\right)} \right] \tag{22}$$

$$Q_i = v \frac{(S_i - S^-)}{(S^+ - S^-)} + (1 - v) \frac{(R_i - R^-)}{(R^+ - R^-)} \tag{23}$$

where $S^+ = \max_i S_i$; $S^- = \min_i S_i$; $R^+ = \max_i R_i$; $R^- = \min_i R_i$; v is introduced as weight of the strategy of "the majority of criteria" (or "the maximum group utility"), here suppose that $v = 0.5$.

- **Step 3:** Rank the alternatives, sorting by the values R, S and Q in descending order. The results are three ranking lists.
- **Step 4:** Based on the VIKOR method, the alternative that has minimum Q_i is the best alternative and it is chosen as compromise solution if the two conditions that mentioned in VIKOR method are satisfied.

4. Case analysis

The selection of a loading–hauling system for a hypothetical iron ore open pit mine was evaluated. Three potential transportation system alternatives have been evaluated that included the shovel-truck (A_1), shovel-truck-in-pit crusher-belt conveyor (A_2) and loader truck (A_3) systems.

As shown in Fig. 1, the top level and the lowest level of the hierarchy denote the overall objective (selecting the suitable loading–haulage equipment in open pit mine) and the candidates, respectively. The seven main criteria namely operating cost, capital cost, working condition, haul distance, reliability, productivity and useful life were included in second level.

4.1. Weighting criteria by AHP-entropy method for loading–haulage equipment selection

An evaluation team of six members who are frequently involved in equipment selection in the particular open pit mine operation was used. The team members included the two sales managers of famous companies in Iran, two mine planning engineers and two academic professors. It deserved mention; all of them have equal impression in group decision making process.

Seven main criteria considered in this study that two of them are interval numbers (capital cost and operating cost), two of them are linguistic terms (working condition and reliability), one of them is crisp value (haul distance) and others are fuzzy numbers (productivity and useful life). Table 3 is showing three attributes are the smaller the better type criteria (operating cost, capital cost and haul distance) and four attributes are the larger the better type criteria.

By using Table 2 and Eqs. (10)–(15), normalized decision-making matrix calculated as follow (Table 4):

Due to complex calculations of entropy method for fuzzy and interval number, traditional entropy method for deterministic number was applied in this step. Therefore, average value of fuzzy and interval numbers was computed and results for entropy weighting method were summarized in Table 5.

As noted in Table 5, capital cost and operating cost have larger weight than other attributes and in contrast, reliability and haul distance weight are very small because as mentioned before if all alternatives are the same in relation to a specific attribute then that attribute should be eliminated because it transmits no information about decision-makers preferences.

By using Table 1, expert team calculated criteria weighting by AHP method. Also, combination weight of entropy and AHP method were calculated by using Eq. (9) and results are given in Table 6.

In next step, positive ideal solution (f^+) and negative ideal solution (f^-) from normalized decision matrix are calculated by Eqs. (16) and (17). Results are summarized in Table 7.

The value of R, S and Q are calculated for all alternatives in Table 8.

The ranking of the alternatives by R, S and Q in descending order is shown in Table 9.

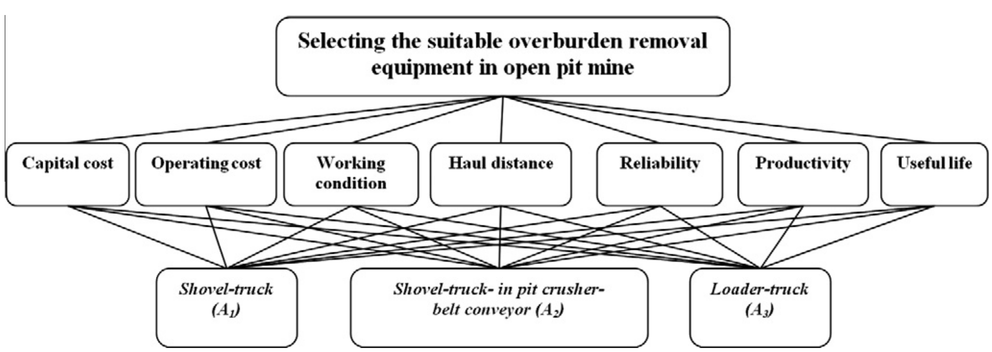

Fig. 1. AHP model for loading–hauling system selection.

Table 3
Evaluation value of loading–haulage system in hypothetical iron ore mine.

	Operating cost ($/t)	Capital cost (million $)	Working condition	Haul distance (km)	Reliability	Productivity (million t /year)	Useful life (thousand (h))
A_1	[4,4.5]	[3,4]	Normal	2	Good	(3.8,4.0,4.2)	(26,28,30)
A_2	[3,3.5]	[4.6,7]	Very good	1.6	Normal	(4.2,4.5,4.8)	(22,24,26)
A_3	[4.5,5.5]	[2.5,3.5]	Good	2	Good	(2.8,3,3.2)	(20,21,23)

Table 4
Normalized decision matrix.

	Operating cost	Capital cost	Working condition	Haul distance	Reliability	Productivity	Useful life
A_1	[0.67,0.75]	[0.63,0.83]	(0.50,0.63,0.75)	0.80	(0.71,0.86,1.00)	(0.79,0.83,0.88)	(0.87,0.93,1.00)
A_2	[0.86,1.00]	[0.36,0.54]	(0.75,0.88,1.00)	1.00	(0.57,0.71,0.86)	(0.88,0.94,1.00)	(0.73,0.80,0.87)
A_3	[0.55,0.67]	[0.71,1.00]	(0.63,0.75,0.88)	0.80	(0.71,0.86,1.00)	(0.58,0.63,0.67)	(0.67,0.70,0.77)

Table 5
Criteria weighting by entropy method.

	Operating cost	Capital cost	Working condition	Haul distance	Reliability	Productivity	Useful life
E_j	0.986	0.970	0.992	0.995	0.997	0.988	0.994
d_j	0.014	0.030	0.008	0.005	0.003	0.012	0.006
w_j	0.182	0.377	0.106	0.066	0.040	0.155	0.073

Table 6
Combination of AHP and entropy method for criteria weighting.

	Operating cost	Capital cost	Working condition	Haul distance	Reliability	Productivity	Useful life
Entropy method	0.182	0.377	0.106	0.066	0.040	0.155	0.073
AHP method	0.200	0.160	0.134	0.065	0.160	0.143	0.138
AHP and entropy	0.236	0.391	0.093	0.028	0.042	0.144	0.066

Table 7
Positive ideal solution and negative ideal solution.

	Operating cost	Capital cost	Working condition	Haul distance	Reliability	Productivity	Useful life
f^{+}	[0.86, 1.00]	[0.71, 1.00]	(0.75, 0.88, 1.00)	1.00	(0.71, 0.86, 1.00)	(0.88, 0.94, 1.00)	(0.87, 0.93, 1.00)
f^{-}	[0.55, 0.67]	[0.36, 0.54]	(0.50, 0.63, 0.75)	0.80	(0.57, 0.71, 0.86)	(0.58, 0.63, 0.67)	(0.67, 0.70, 0.77)

Table 8
The values of S, R and Q for all alternatives.

	A_1	A_2	A_3
S	0.459	0.473	0.520
R	0.163	0.391	0.236
Q	0.000	0.608	0.661

Table 9
The ranking of the alternatives by S, R and Q in descending order.

	Ranking alternatives		
	1	2	3
By S	A_1	A_2	A_3
By R	A_1	A_3	A_2
By Q	A_1	A_2	A_3

As we see in Table 9, the alternative A_1 is the best ranked by Q. Also the conditions one and two are satisfied $Q_{A_1} - Q_{A_2} > \frac{1}{(3-1)}$ and A_1 is best ranked by S and R. So A_1 (shovel-truck system) is the best choice.

5. Conclusion

The open pit equipment selection problem is a strategic issue and has significant impacts to the open-pit design and production planning. Most of exiting open pit equipment selection rely on objective input data, with little or no subjective judgment, or focus on a single parameter; and therefore lead to a poor equipment selection due to the MADM nature of equipment selection problem.

Mining equipment selection problem is often influenced by uncertainty in practice; also because of the fact that determining the exact values of the attributes is difficult or impossible, it is more appropriate to consider them as interval numbers, fuzzy numbers or linguistic terms. In this paper an extension of the VIKOR, a recently introduced MADM method, in all type of data environment (crisp, fuzzy, linguistic and interval numbers) is proposed to deal with the both qualitative and quantitative criteria and select the suitable loading–haulage system in open pit mine effectively. The proposed method is very flexible. This method enables us to asses and rank alternatives. Also the proposed method for equipment selection in fuzzy and interval numbers environment provide a systematic approach which can be easily extended to deal with other mining engineering selection problems.

References

Aghajani, A., & Osanloo, M. (2007). Application of AHP-TOPSIS method for loading–haulage equipment selection in open pit mines. In *XXVII international mining convention, Mexico* (pp. 12–16).

Aghajani Bazzazi, A., Osanloo, M., & Karimi, B. (2009). Optimal open pit mining equipment selection using fuzzy multiple attribute decision making approach. *Archive of Mining Science, 54*, 301–320.

Bandopadhyay, S., & Venkatasubramanian, P. (1987). Expert systems as decision aid in surface mine equipment selection. *International Journal of Mining, Reclamation and Environment, 1*, 59–165.

Bascetin, A. (2004). An application of the analytic hierarchy process in equipment selection at Orhaneli open pit coal mine. *Mining Technology: Transactions of the Institute of Mining and Metallurgy, Section A, 113*, 192–199.

Büyüközkan, G., & Ruan, D. (2008). Evaluation of software development projects using a fuzzy multi-criteria decision approach. *Mathematics and Computers in Simulation, 77*, 464–475.

Cebesory, T. (1997). Surface mining equipment cost analysis with a developed linear break even model. *International Journal of Mining, Reclamation and Environment, 11*, 53–58.

Celebi, N. (1998). An equipment selection and cost analysis system for open pit coal mines. *International Journal of Mining, Reclamation and Environment, 12*, 181–187.

Denby, B., & Schofield, D. (1990). Application of expert systems in equipment selection for surface design. *International Journal of Mining, Reclamation and Environment, 4*, 165–171.

Hall, R., & Daneshmand, K. (2003). Reliability modeling of surface mining equipment: Data gathering and analysis methodologies. *International Journal of Mining, Reclamation and Environment, 17*, 139–155.

Hrebar, M. J. (1990). Preliminary dragline selection for surface coal mining operation. In *Second international conference on mine planning and equipment selection, Canada* (pp. 133–143).

Hwang, C. L., & Yoon, K. (1981). *Multiple attribute decision making methods and applications: A state of the art survey*. New York: Springer-Verlag.

Jahanshahloo, G. R., Hosseinzadeh, F., & Izadikhah, M. (2006). An algorithmic method to extend TOPSIS for decision making problems with interval data. *Applied Mathematics and Computation, 175*, 1375–1384.

Moore, R. E. (1979). *Method and application of interval analysis*. Philadelphia: SIAM.

Opricovic, S., & Tzeng, G. H. (2002). Multicriteria planning of post-earthquake sustainable reconstruction. *Computer-aided Civil and Infrastructure Engineering, 17*, 211–220.

Opricovic, S., & Tzeng, G. H. (2003). Fuzzy multicriteria model for post-earthquake land use planning. *Natural Hazards Review, 4*, 59–64.

Opricovic, S., & Tzeng, G. H. (2004). Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. *European Journal of Operational Research, 156*, 445–455.

Opricovic, S., & Tzeng, G. H. (2007). Extended VIKOR method in comparison with outranking methods. *European Journal of Operational Research, 178*, 514–529.

Saaty, T. L. (1990). *The analytic hierarchy process*. New York: McGraw-Hill.

Saaty, T. L., & Vargas, L. G. (1994). *Decision making in economic, political, social, and technological environments with the analytic hierarchy process*. Pittsburgh: RWS Publications.

Samanta, B., Sarkar, B., & Mukherjee, S. (2002). Selection of opencast mining equipment by a multi-criteria decision-making process. *Mining Technology: Transactions of the Institute of Mining and Metallurgy, Section A, 111*, 136–142.

Sayadi, M. K., Heydari, M., & Shahanaghi, K. (2009). Extension of VIKOR method for decision making problem with interval numbers. *Applied Mathematical Modelling, 33*, 2257–2262.

Sevim, H., & Sharma, G. (1991). Comparative economic analysis of transportation systems in surface coal mines. *International Journal of Mining, Reclamation and Environment, 5*, 17–23.

Shannon, C. E., & Weaver, W. (1947). *The mathematical theory of communication*. Urbana: University of Illinois Press.

Tzeng, G. H., Lin, C. W., & Opricovic, S. (2005). Multi-criteria analysis of alternative-fuel buses for public transportation. *Energy Policy, 33*, 1373–1383.

Tzeng, G. H., Teng, M. H., Chen, J. J., & Opricovic, S. (2002). Multicriteria selection for a restaurant location in Taipei. *International Journal of Hospitality Management, 21*, 171–187.

Tzeng, G. H., Tsaur, S. H., Laiw, Y. D., & Opricovic, S. (2002). Multicriteria analysis of environmental quality in Taipei: Public preferences and improvement strategies. *Journal of Environmental Management, 65*, 109–120.

Ye, F., & Li, Y. N. (2009). Group multi-attribute decision model to partner selection in the formation of virtual enterprise under incomplete information. *Expert Systems with Applications, 36*, 9350–9357.

Yu, P. L. (1973). A class of solutions for group decision problems. *Management Science, 19*, 936–946.

Zeleny, M. (1982). *Multiple criteria decision making*. New York: McGraw-Hill.

Zhu, H., Liu, S. Y., & Fang, X. R. (2007). Method for uncertain multi-attribute decision making with preference information in the form of interval numbers complementary judgment matrix. *Journal of Systems Engineering and Electronics, 18*, 265–269.