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Equipment Selection Using Fuzzy Multi Criteria Decision Making Model: Key Study of Gole Gohar Iron Mine

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Loading and hauling contribute significantly towards expenses in surface mines. Thus selecting the most suitable system which minimizes the cost per ton and meets production needs is one of the main concerns of mine design and planning. It is also at times difficult to select the optimum equipment, as there are many possible options and influencing factors in selecting a system. Furthermore, some of these factors can be either quantitative or qualitative. As a result, the use of multi attribute decision making methods can be useful. In this article, the selection of the equipment fleet of Gole Gohar mine was done though four stages. First, feasible technical and operational options were determined. Next, the weights of influential criteria were determined using a hybrid method of fuzzy analytical hierarchical process and analytical network process. Then, the alternative preference rating matrix was calculated using fuzzy TOPSIS method and finally, the hierarchy of alternatives was decided by combining the available weight and ranking matrix. This model considers all affecting parameters simultaneously and facilitates making a reasonable decision about the most appropriate material handling equipment. For the purpose of evaluation in this method, the cost of each equipment fleet was assessed and compared using the traditional method. Results show that the use of the fleet of cable shovel and truck is the most economical loading and hauling system. The results not only indicate that proposed model offers chances to choose the best alternative among possible loading and hauling systems, but also help equipment managers to make an accurate and reasonable decision regarding all effective parameters.

Keywords: MCDM, Fuzzy Sets, AHP, ANP, TOPSIS, Integrated Model, Equipment, Selection.

Introduction

The selection of the loading and hauling equipment fleet is one of the most important phases of design in surface mines due to the fact that some operational parameters such as bench height and width when selected impact considerably on the size of available equipment. Moreover, these operations account for 65 percent of the total operational costs of surface mines, so selecting the right equipment can significantly reduce costs. To select the proper surface mining equipment fleet, three steps should be taken. Firstly, related to the operational conditions of the mine, the available types of equipment are determined. Then loading equipment specifications are determined and the appropriate hauling equipment is then selected according to bucket capacity and dumping height of loading equipment. Finally, based on annual production forecasts, the required number of each machine can be calculated.

There is a wide range of equipment that can be used for loading and hauling in surface mines. In order to select the optimal equipment, all possible options should be analyzed. The factors affecting the choice of equipment can be classified into four groups, these being technical specifications, operational efficiency, capital and operating costs. Some of these factors are quantitative while others are qualitative which require a measurement methodology in order to make them quantifiable. Incorporated with the selection of the most efficient equipment, there should be also sufficient knowledge and necessary skill to efficiently use the equipment. These complexities create an environment which makes it difficult to analyze simultaneously all relevant factors.

Different methodologies have been used to select surface mining equipment including but not limited to expert systems (Bandopadhyay and Venkatasubramanian, 1987; Denby and Schofield, 1990; Amirkhanian and Baker, 1992; Ganguli and Bandopadhyay, 2002), mathematical modeling (Fishler, 1987; Çelebi, 1998), computerized modeling (Chan and Harris, 1989; Haidar, 1999; Alkass et al. 2003), simulations (Sturgul, 2000), queuing theory (Alkass et al. 2003), and multi attribute decision making (Samanta, 2002; Bascetin, 2003; Bascetin, 2004; Kazakidis, 2004; Kulak, 2005; Shapita and Goldenberg, 2005; Bascetin et al. 2006; Tayeb 2007; Aghajani and Osanloo, 2007; Aghajani et al. 2009; Aghajani et al, 2011).

There is no well–defined process for selection of the most appropriate type of loading equipment for open–pit mines, because not only various options should be considered as potential loading systems, but also there are a large number of effective parameters which are in conflict with each other. Furthermore, both qualitative and quantitative sorts of data are expected for this selection. For these reasons, the selection of a suitable loading system is a complex problem which requires the traditional single–criterion decision making method. Due to the inability of conventional approach in handling the uncertain and imprecise decision–making problems this method is often criticized. According to the capability of fuzzy method in handling the inherent uncertainties, this problem can be considered as a fuzzy multi attribute decision making (MADM) problem. The main objective of this paper is to present a powerful fuzzy MADM tool for making an appropriate decision in complex problems featuring uncertainty and contradictory goals. In this approach, a hybrid model of fuzzy AHP and ANP was used for weighting the parameters. AHP method is widely useful due to its inherent ability to handle both qualitative and quantitative criteria and the combination of AHP and fuzzy logic solves the problem of existing uncertainties. Moreover, ANP is used because there are nonlinear relationships among hierarchical levels which make some problems in implementation of AHP technique. Then, the necessary loading and hauling equipment of Gole Gohar surface mine were selected using the TOPSIS method under a fuzzy environment due to its rational structure, simplicity, good computational efficiency and capability to determine the relative performance for each option in a simple mathematical form.

Fundamental

Fuzzy sets

In case there is an indeterminate relationship among the available criteria or different alternatives and these relationships cannot be explained using the distinct numbers, it is helpful to use the fuzzy theory. Fuzzy theory was introduced by Zadeh in 1965.

If you consider $\tilde{A} = (a_1, a_2, a_3)$ a triangular fuzzy number in which a_1, a_2 and a_3 are distinct numbers and considering $a_1 \le a_2 \le a_3$ then the membership function $f_{\tilde{A}}(x)$ is:

$$f_{\tilde{A}}(x) = \begin{cases} 0 & , \quad x < a_1 \\ (x - a_1)/(x_2 - a_1) \, , & a_1 \le x \le a_2 \\ (a_3 - x)/(a_3 - a_2) \, , & a_2 \le x \le a_3 \\ 0 & , \quad x > a_3 \end{cases} \qquad (1)$$

The distance between the two phase number $\tilde{A}$ and $\tilde{B}$ is:

$$d(\tilde{A}, \tilde{B}) = \sqrt{\frac{1}{3}\left[(a1 - b1)^2 + (a2 - b2)^2 + (a3 - b3)^2\right]} \qquad (2)$$

The matrix form of the multi–criteria decision making problems is as follows:

$$\tilde{D} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & & C_n \end{array} \\ \begin{pmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{23} \\ \vdots & \vdots & & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{32} & \cdots & \tilde{x}_{mn} \end{pmatrix} \end{array} \qquad (3)$$

$$\tilde{W} = \tilde{w}_1, \tilde{w}_2, \, \dots \, , \tilde{w}_n \qquad (4)$$

Where $\tilde{x}_i$ in the previous matrix is the performance rating of the ith alternatives to the jth criterion which is expressed by a triangular fuzzy number and $\tilde{w}_j$ which is a fuzzy number and describes the weight of the jth factor.

The normalized fuzzy matrix is shown by $\tilde{R}$ which is derived from the following equation:

$$\tilde{v} = \left[\tilde{v}_{ij}\right] = \left[\tilde{w}_j \tilde{r}_{ij}\right] \qquad i=1,2,\dots,m \quad ; \; j=1,2,\dots,n \qquad (5)$$

$$\tilde{R} = \left[r_{ij}\right]_{m \times n} \qquad (6)$$

Analytical Hierarchical Process (AHP)

The AHP was first introduced by Saaty in 1980. AHP decomposes difficult and complicated problems into simpler forms and then solves them. This method has recently become very popular in solving economic and engineering problems. This methodology helps decision makers prioritize their goals according to existing knowledge, experience and given assumptions. The AHP method provides a structured framework for setting priorities on each level of the hierarchy using pair–wise comparisons that are quantified using 1–9 scales in Table 1. Three principal concepts of AHP method are: defining the analytical hierarchy process, then determining priorities, and the logical consistency of the assumptions. The AHP algorithm is structured into four steps: Step 1: defining the decision problem within the hierarchical model, Step 2: making pair–wise comparisons and obtaining the assumption matrix, Step 3: assess mine specific priorities and consistency of comparisons, Step 4: aggregation of mine specific priorities (Ramanathan, 2001).

Table 1

Pair–wise comparison scale and example (Saaty, 1980)

Intensity	Definition
1	Equal importance
3	Moderate importance of one over another
5	Essential or strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values
Reciprocals	Reciprocals for inverse comparison

The inconsistency rate is determined by adopting the following steps:

a. The weighted sum vector (WSV) should be analyzed by multiplying paired comparison matrix by the relative weight vector:

$$WSV = D \times W \qquad (7)$$

b. The Consistency Vector (CV) should be analyzed by dividing the elements of the weighted sum vector by the relative weights vector.

c. Determining the maximum eigenvector of pair–wise comparison matrix ($\lambda_{\max}$). For this we need to determine the average of the consistency vector factors.

d. Determining the second Inconsistency Index (II) by using following equation:

$$II = \frac{\lambda_{\max} - n}{n-1} \qquad (8)$$

e. Determining the Inconsistency Rate (IR) from the following equation:

$$IR = \frac{II}{IRI} \qquad (9)$$

IRI is Inconsistency Random Index which is derived from the table 2. This table is based on the simulation that Saaty (1980, 2000) provided with average consistencies (IRI values) of randomly generated matrices (up to size 11×11) for a sample size of 500.

Table 2

Inconsistency Random Index table

n	1	2	3	4	5	6	7	8	9	10
IRI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

In case the inconsistency rate is smaller or equal to 0.1, pair–wise comparisons are consistent and the process can be continued, otherwise the decision maker should reconsider pair–wise comparisons.

Analytical Network Process (ANP)

The ANP, also introduced by Saaty, is a generalization of the AHP (Saaty, 1996). This methodology employs the decision making process aligned to scenarios affected by the multi–agent independent factors which up until now were not addressed within the hierarchical structures due to system complexities. However, not only does the ANP not constrain a special hierarchical structure, it also models the problem by allowing for feedback to be introduced. The system contains feedback mechanisms that can be shown by a network in which nodes show the levels or components. The structural difference between hierarchical structure and network structure is shown in Figure1.

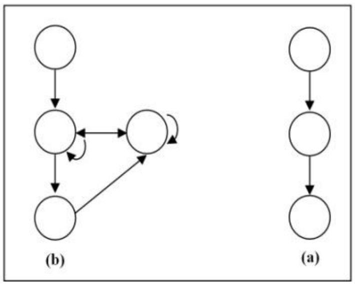

Figure 1. Structural different between hiererchical and network (Chung , Lee, and Pearn, 2005): (a) hiererchical; (b) network

The existing elements of each node (or level) may affect the elements of other nodes partially or entirely. A network may affect certain main, middle and lower nodes. The existing relationships in the net are shown by arrows and the direction of arrows determines the direction of dependence. ANP consists of four main steps (Saaty, 1996; Chung *et al.*, 2005).

Step 1: Model construction and problem definition: the problem should be clearly characterized and divided into logical structure such as the network. The mentioned structure can be arrived at using the decision maker's knowledge and experience or appropriate creative think tank such as brainstorming. Figure 1 (b) reflects network structure.

Step 2: Pair–wise comparisons matrices and priority vectors: Decision making elements are compared as pairs in each section according to their level of importance within the controlling factors. Sections are then compared as pairs based on their impact on the agreed objectives in the ANP. Decision makers are then asked to verify the effect of each on the higher level factors. Furthermore, should the elements not be mutually exclusive, the interrelationship of the elements is shown by pair–wise comparisons and finding eigenvector of each element. The performance rating is obtained by utilizing a relative scale approach.

Step 3: Supermatrix formation: the concept of the super matrix is similar to the Markov chain process (Saaty, 1996). This matrix can limit the coefficients to calculate all priorities and, as a result, the cumulative effect of each element on other elements is in balance. When the network, ignoring its goal, consists of two clusters named factors and alternatives, the proposed matrix by Saaty and Takizawa in 1986 can be used to face the relationship of elements in the system. They proposed that in order to know the general priorities of the system with interaction, priorities should be included in special columns of the matrix which is the super matrix.

The super matrix is actually a classified matrix in which each part indicates the interrelationship between two groups in the system. Imagine the system has Ck components of decision making with k=1, 2… n and each component has m elements which are shown by e_{k1}, e_{k2},…, e_{kn} (Figure 2).

Figure 2. Super matrix

As a result the matrix will be (Saaty, 1996):

$$w_h = \begin{pmatrix} 0 & 0 & 0 \\ w_{21} & 0 & 0 \\ 0 & w_{32} & I \end{pmatrix} \qquad (10)$$

In which w_{21} is a vector which represents the impact of the goal on the criteria, w_{32} is the criteria influence matrix on each of the alternatives and *I* represent the identity matrix and zeros express those independent elements that are mutually exclusive. If the criteria are interrelated, the super matrix will be as follows in which w_{22} indicates this interdependency (Saaty, 1996):

$$w_n = \begin{pmatrix} 0 & 0 & 0 \\ w_{21} & w_{22} & 0 \\ 0 & w_{32} & I \end{pmatrix} \qquad (11)$$

Step 4: Selection of best alternatives: If the prepared super matrix from the previous stage covers the entire network, the priority weights will be found in the alternatives column of a normalized super matrix. Eventually, the best alternative will have the largest priority.

Fuzzy TOPSIS method

TOPSIS was first introduced by Hwang and Yoon (1981) and has been applied for the technical problem solution and assessment for long time (Zavadskas 1987). This methodology will produce a result whereby, the selected alternative should have the lowest distance to the positive ideal solution (the best possible condition) and the highest distance to the negative ideal solution (the worst possible solution). The ideal solution (also called positive ideal solution) is a solution that maximizes the benefit criteria and minimizes the cost criteria, whereas the negative ideal solution (also called anti–ideal solution) maximizes the cost criteria and minimizes the benefit criteria (Ataei *et al.*, 2008). Recently the TOPSIS method has been widely applied (Zavadskas and Antucheviciene, 2006; Liaudanskiene *et al.*, 2009; Rudzianskaitė–Kvaraciejienė et al., 2010; Zavadskas *et al.*, 2010 a, b; Antucheviciene *et al.*, 2010; Cokorilo et al., 2010; Lashgari *et al.*, 2011; Tupenaite *et al.*, 2010; Podvezko *et al.*, 2010; Fouladgar *et al.*, 2011; Han and Liu, 2011; Azimi *et al*., 2011, Liu, 2011).

It is inherent in the TOPSIS methodology that the sufficiency of each criterion rises and falls regularly. TOPSIS to the fuzzy environment, developed by Chen (2000), is here used as a robust tool to manage linguistic judgments of experts and to produce the final ranking of activities. Fuzzy TOPSIS is widely used to solve the MCDM Problems (Wang and Chang, 2007; Kannan *et al.*, 2009; Chamodrakas *et al.*, 2009; Mahdavi *et al.*, 2008; Wang and Lee, 2009; Ashtiani *et al.*, 2009; Torfi *et al.*, 2010; Chen and Lee, 2010; Cavallaro, 2010; Wang and Elhag, 2006; Amiri, 2010; Chen and Tsao, 2008; Yazdani-Chamzini, Yakhchali, 2012; Fouladgar *et al.*, 2012). There are six steps to take to solve the problem in the method:

a. The alternatives must be scored relative to the different criteria also qualitative phrases are used to weight the criteria and normalize the decision matrix in the calculation process. For this reason language variables can be used as fuzzy membership function. Table 3 shows linguistic variables for the criteria weights.

Table 3

Linguistic variables for the criteria weights

Very poor (VP)	(0, 0, 2.5)
poor (P)	(0, 2.5, 5)
moderate (M)	(2.5, 5, 7.5)
good (G)	(5, 7.5, 10)
Very good (VG)	(7.5, 10, 10)

b. The weighted normalized fuzzy matrix with v_{ij} as weighted value is determined, where *i* and *j* are associated with benefit and cost criteria, respectively.

c. The positive ideal solution (A^+) and the negative ideal solution (A^-) are defined as follows:

$$A^+ = (\tilde{v}_1^+, \tilde{v}_2^+, \tilde{v}_3^+, ..., \tilde{v}_n^+) = \max_i \; v_{ij} \Big| (i = 1, 2, ..., n) \qquad (12)$$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \tilde{v}_3^-, ..., \tilde{v}_n^-) = \min_i \; v_{ij} \Big| (i = 1, 2, ..., n) \qquad (13)$$

The optimal values for positive and negative criteria are the largest and smallest respectively and the worst ones are the smallest for positive and the largest for the negative criteria.

d. The Euclidean distance of each alternative from the positive ideal (d_j^+) and the negative ideal (d_j^-) are calculated with the help of the following equations:

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-) \ , \ i = 1, 2, ..., m \tag{14}$$

$$d_i^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^+) \ , \ i = 1, 2, ..., m \tag{15}$$

e. Relative proximity of each alternative to the ideal solution is determined as following:

$$CL = \frac{d_i^-}{d_i^+ + d_i^-} \tag{16}$$

f. The alternatives are ranked according to their relative proximity to the ideal solution. Alternative with the larger CL represents the optimal alternative.

Model

A number of methodologies are predicated on quantitative and objective parameters to decide the best way to choose equipment, and qualitative factors are not always considered. This problem can be solved by using an analytical hierarchical process (AHP). Furthermore, as there is a nonlinear relationship among hierarchical levels, weighting some criteria depends on their numerical value which is not easily done by the AHP. Therefore, it can be useful to apply a hybrid method of the hierarchical and analytical network process (ANP) to solve the problem weighting factors. It can also be useful to apply the fuzzy theory in the weighting process given the uncertainty between criteria and the correlation with alternatives. Therefore, a combination on fuzzy AHP and ANP methods has been used for weighting the criteria. TOPSIS method under fuzzy environment is utilized for ranking of the alternatives because of being simple computations, rational, and results are obtained in shorter time than other methods (Percin, 2009). Figure 3 shows the scheme of research methodology.

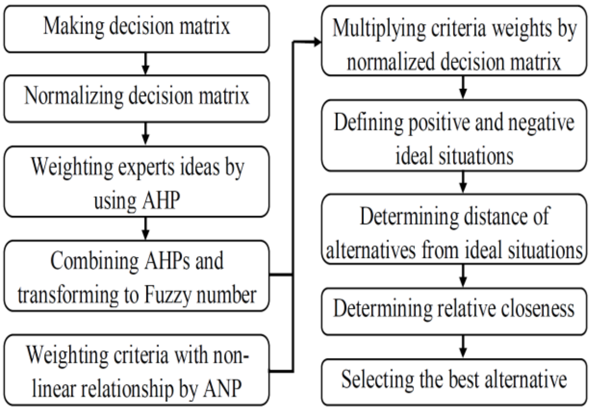

Figure 3. Scheme of research methodology

Gole Gohar surface iron mine (case study)

Gole Gohar mine is located in Kerman province approximately 55 Km south west of the city of Sirjan, between 551150E and 551240E longitudes and 29130N and 29170N latitudes. It is close to the center of a triangle covering Kerman, Shiraz and Bandar Abbas. Geomorphologically, which is a vast arid area and there is a vaporous mountain range to its south, south west. The Gole Gohar deposit is in six separate deposits within 10 Km by 4 Km area, with a total ore reserve of about 1135 million ton. This area is filled with metamorphic rocks of the Paleozoic era including gneiss, schist and amphibolites at the bottom, followed by limestone and dolomite sedimentary rocks of the Mesozoic and Cenozoic eras, overlain by late Quaternary alluvium and alluvial sediments. The iron ore deposit of the area is embedded in the metamorphic rocks (Rouhani and Hojat, 2004). The ore reserve of the mine No.1 is approximately 251 million tons. Table 4 shows brief information intended for rating. Fig.4 shows the location of Gole Gohar iron ore complex and Mine No.1.

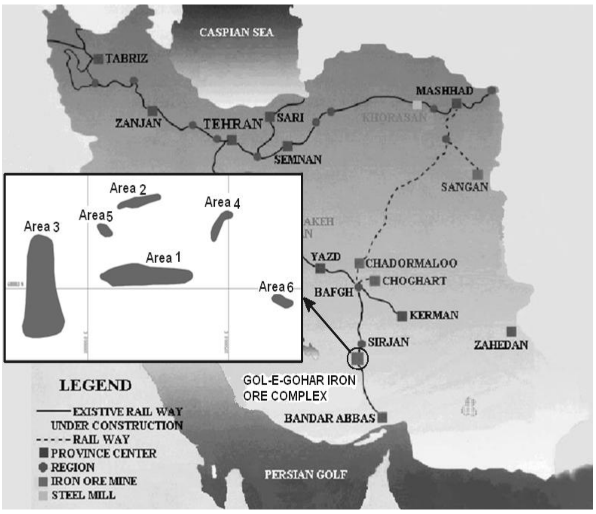

Figure 4. Gole Gohar Iron Mine (Rouhani and Hojat, 2004)

Table 4

Iron mine information intended for Rating

Reserve	251 million ton
Daily production rate	29000 ton
Type of mineral	Magnetite with 69% assay
Active workday	335 days per year and 2.5
Bench height	15 meter
Working bench width	25 meter
Terms of working floor	Stable for each loading
Breaking size of blasting	30– 40 centimeter
Inflation factor	1.3
Average rolling resistance	2.5% (assumed)
Swell factor	0.95
Moisture	70% (in +30 centigrade)
Weather condition	Warm and dry
Truck type used in mine	Caterpillar 777D

The hierarchical structure for selecting of the loading equipment is shown in Fig.5. In this structure, the aim is to choose the best loading and hauling equipment. The main decision making criteria are technical parameters, operational parameters along with operational and capital costs and each factor is divided into several sub criteria. In order to expert's idea, 30 parameters were considered to making this decision.

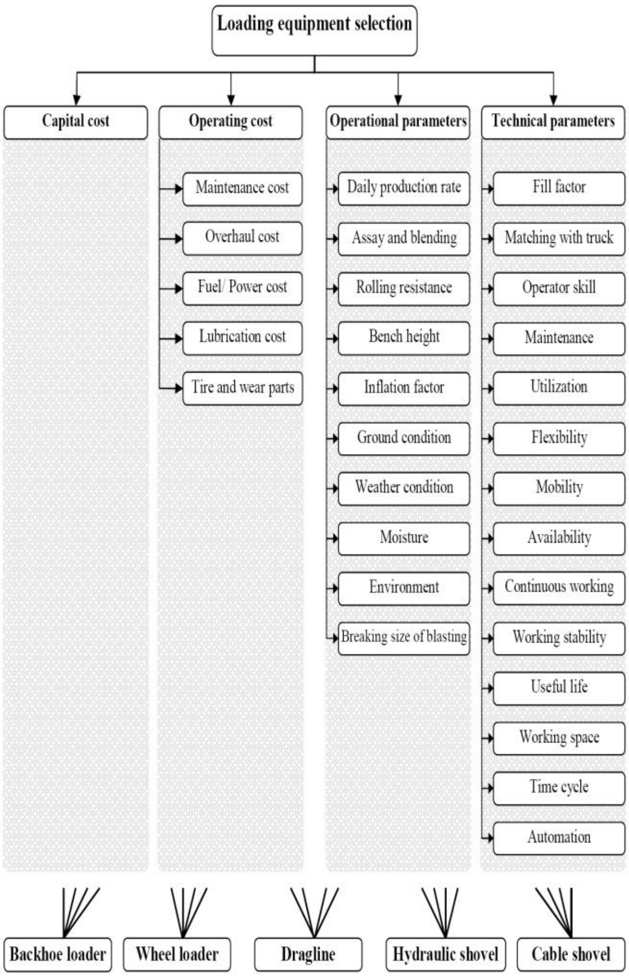

Figure 5. Hierarchy for loading equipment selection

ANP and AHP under fuzzy environment were used to weight factors. At first, a questionnaire to compare paired factors was prepared and given to employees/contractors with the relevant knowledge and skill base. Then, AHP was used to determine the weight of each factor per collated questionnaire results. There were 20 questionnaires completed as the sample size for the study, 20 AHP matrixes were derived and weightings were determined. The inconsistency rate was less than 0.1 in all AHPs. Then, using the following equation, fuzzy weights were determined.

$$(\tilde{w}_l) = (Lw_i, Mw_i, Uw_i) \tag{17}$$

$$Lw_i = \min_k \; Lw_{ik} \quad , \mathrm{Mw}_i = \frac{1}{K}\sum_{k=1}^{K} Mw_{ik} \; , \mathrm{Uw}_i = \max_k \; Uw_{ik} \tag{18}$$

In which w_L is the weight derived from AHP method for L^{th} factor and k is the sample size. Final results are shown in table 5.

Table 5

Total fuzzy AHP matrix from expert's opinions

	Total fuzzy weight
Daily production rate	(0.52, 0.79, 0.91)
Assay and blending	(0.001, 0.31, 0.57)
Breaking size of blasting	(0.002, 0.45, 0.72)
Rolling resistance	(0.001, 0.40, 0.66)
Bench height	(0.66, 0.91, 1.00)
Inflation factor	(0.003, 0.45, 0.72)
Ground condition	(0.57, 0.83, 1.00)
Weather condition	(0.001, 0.45, 0.72)
Moisture	(0.001, 0.45, 0.72)
Environment	(0.25, 0.50, 0.75)
Fill factor	(0.002, 0.52, 0.79)
Matching with truck	(0.31, 0.57, 0.83)
Flexibility	(0.50, 0.75, 1.00)
Operator skill	(0.66, 0.91, 1.00)
Maintenance	(0.40, 0.66, 0.91)
Utilization	(0.75, 1.00, 1.00)
Mobility	(0.57, 0.83, 1.00)
Availability	(0.45, 0.72, 0.91)
Continuous working	(0.40, 0.66, 0.91)
Working stability	(0.50, 0.75, 1.00)
Useful life	(0.003, 0.57, 0.79)
Working space	(0.001, 0.63, 0.79)
Time cycle	(0.001, 0.57, 0.79)
Automation	(0.36, 0.63, 0.83)
Operational parameters	(0.45,0.72,0.91)
Technical parameters	(0.36,0.63,0.83)
Operating cost	(0.52,0.79,0.91)
Capital cost	(0.45,0.72,0.91)

AHP cannot be used to determine the precise weight of sub–criteria related to operating costs as the weight of each sub–criterion is dependent on its numerical value. Thus, ANP could be used to solve this problem as it is helpful to solve the problem of non–linear dependencies. Table 6 and 7 show the costs related to the loading equipment (as ANP inputs) and the total weight matrix of operating costs sub–criteria, respectively. Then, alternatives were scored according to different criteria and then weighted (Table 8).

Table 6

Operating costs related to loading equipment

	Fuel/ power (C1)	Overhaul (C2)	Maintenance (C3)	Lubrication (C4)	Tire and wear parts (C5)
Hydraulic shovel (A1)	76.4	23.44	35.15	10.67	5.55
Cable shovel (A2)	22.33	18.05	27.08	9.14	8.32
Dragline (A3)	37.2	45.93	85.29	29.71	23.04
Wheel loader (A4)	47.31	11.92	22.13	9.33	28.2
Backhoe loader (A5)	56.55	21.76	32.65	9.37	4.56

Table 7

Total weight matrix of operating costs sub–criteria from ANP

Element	weight
Fuel/ power	0.36
Overhaul	0.169
Maintenance	0.271
Lubrication	0.092
Tire and wear parts	0.108
Hydraulic shovel	0.169
Cable shovel	0.277
Dragline	0.129
Wheel loader	0.227
Backhoe loader	0.198

Table 8

Criteria weight matrix and weight of alternatives against criteria

	Hydraulic shovel	Cable shovel	Dragline	Wheel loader	Backhoe loader
Daily production rate	(0.638, 0.891, 1.0)	(0.588, 0.841, 1.000)	(0.000, 0.379, 0.638)	(0.000, 0.411, 0.675)	(0.000, 0.411, 0.660)
Assay and blending	(0.0, 0.715, 0.871)	(0.000, 0.638, 0.871)	(0.000, 0.435, 0.675)	(0.000, 0.623, 0.822)	(0.000, 0.623, 0.822)
Breaking size of blasting	(0.588, 0.841, 1.0)	(0.588, 0.841, 1.000)	(0.000, 0.623, 0.822)	(0.000, 0.588, 0.822)	(0.000, 0.623, 0.822)
Rolling resistance	(0.483, 0.758, 0.891)	(0.555, 0.822, 0.944)	(0.000, 0.588, 0.822)	(0.000, 0.555, 0.822)	(0.000, 0.588, 0.822)
Bench height	(0.512, 0.776, 0.944)	(0.692, 0.944, 1.000)	(0.000, 0.588, 0.822)	(0.000, 0.411, 0.660)	(0.000, 0.472, 0.715)
Inflation factor	(0.588, 0.841, 1.000)	(0.512, 0.776, 0.944)	(0.000, 0.715, 0.871)	(0.000, 0.512, 0.758)	(0.542, 0.794, 1.000)
Ground condition	(0.588, 0.841, 1.000)	(0.542, 0.794, 1.000)	(0.446, 0.715, 0.891)	(0.588, 0.841, 1.000)	(0.638, 0.891, 1.000)
Weather condition	(0.472, 0.733, 0.944)	(0.512, 0.776, 0.944)	(0.358, 0.623, 0.841)	(0.388, 0.660, 0.841)	(0.446, 0.715, 0.891)
Moisture	(0.588, 0.841, 1.000)	(0.588, 0.841, 1.000)	(0.358, 0.623, 0.841)	(0.411, 0.675, 0.891)	(0.358, 0.623, 0.841)
Environment	(0.000, 0.472, 0.715)	(0.000, 0.446, 0.715)	(0.000, 0.000, 0.555)	(0.000, 0.000, 0.588)	(0.000, 0.435, 0.675)
Fill factor	(0.638, 0.891, 1.000)	(0.638, 0.891, 1.000)	(0.411, 0.675, 0.891)	(0.472, 0.733, 0.944)	(0.411, 0.675, 0.891)
Matching with truck	(0.500, 0.750, 1.000)	(0.500, 0.750, 1.000)	(0.250, 0.500, 0.750)	(0.750, 1.000, 1.000)	(0.750, 1.000, 1.000)
Flexibility	(0.000, 0.675, 0.871)	(0.435, 0.692, 0.944)	(0.000, 0.500, 0.733)	(0.411, 0.675, 0.891)	(0.000, 0.574, 0.776)
Operator skill	(0.542, 0.794, 1.000)	(0.472, 0.733, 0.944)	(0.000, 0.542, 0.776)	(0.472, 0.733, 0.944)	(0.588, 0.841, 1.000)
Maintenance	(0.472, 0.733, 0.944)	(0.512, 0.776, 0.944)	(0.379, 0.638, 0.891)	(0.472, 0.733, 0.944)	(0.500, 0.750, 1.000)
Utilization	(0.500, 0.750, 1.00)	(0.692, 0.944, 1.000)	(0.388, 0.660, 0.841)	(0.411, 0.675, 0.891)	(0.411, 0.675, 0.891)
Mobility	(0.000, 0.638, 0.871)	(0.000, 0.588, 0.822)	(0.000, 0.512, 0.776)	(0.542, 0.794, 1.000)	(0.000, 0.638, 0.871)
Availability	(0.435, 0.692, 0.944)	(0.411, 0.675, 0.891)	(0.000, 0.542, 0.776)	(0.411, 0.675, 0.891)	(0.000, 0.588, 0.822)
Continuous working	(0.512, 0.776, 0.944)	(0.435, 0.692, 0.944)	(0.512, 0.776, 0.944)	(0.000, 0.512, 0.776)	(0.000, 0.542, 0.776)
Working stability	(0.411, 0.675, 0.891)	(0.542, 0.794, 1.000)	(0.411, 0.675, 0.891)	(0.330, 0.588, 0.841)	(0.000, 0.542, 0.776)
Useful life	(0.435, 0.692, 0.944)	(0.588, 0.841, 1.000)	(0.555, 0.822, 0.944)	(0.330, 0.588, 0.841)	(0.000, 0.472, 0.733)
Working space	(0.000, 0.555, 0.822)	(0.411, 0.675, 0.891)	(0.000, 0.623, 0.822)	(0.512, 0.776, 0.944)	(0.555, 0.822, 0.944)
Time cycle	(0.435, 0.692, 0.944)	(0.555, 0.822, 0.944)	(0.358, 0.623, 0.841)	(0.000, 0.512, 0.776)	(0.000, 0.472, 0.715)
Automation	(0.000, 0.483, 0.758)	(0.000, 0.574, 0.758)	(0.000, 0.000, 0.675)	(0.000, 0.446, 0.715)	(0.000, 0.379, 0.623)
Operational parameters	(0.542, 0.794, 1.000)	(0.542, 0.794, 1.000)	0.000, 0.000, 0.638	(0.000, 0.555, 0.822)	(0.411, 0.675, 0.891)
Technical parameters	(0.588, 0.841, 1.000)	(0.638, 0.891, 1.000)	0.000, 0.512, 0.776	(0.435, 0.692, 0.944)	(0.358, 0.623, 0.841)
Operating cost	(0.411, 0.675, 0.891)	(0.602, 0.871, 0.944)	0.000, 0.435, 0.675	(0.446, 0.715, 0.891)	(0.330, 0.588, 0.841)
Capital cost	(0.000, 0.588, 0.822)	(0.000, 0.512, 0.776)	0.000, 0.000, 0.411	(0.000, 0.660, 0.822)	(0.483, 0.758, 0.891)

By multiplying operating cost items fuzzy weight by the weight of the alternatives from ANP, table 9 has derivatives.

The normalized fuzzy weighted matrix is made in the next stage (Table 10).

Table 9

Fuzzy weight of each alternative per operating costs

Alternatives	Operating costs
A1	(0.087884, 0.134135, 0.153547)
A2	(0.144046, 0.219855, 0.251671)
A3	(0.067083, 0.102387, 0.117204)
A4	(0.118045, 0.18017, 0.206243)
A5	(0.102964, 0.157153, 0.179895)

Table 10

Normalized fuzzy weighted matrix

	Hydraulic shovel	Cable shovel	Dragline	Wheel loader	Backhoe loader
Daily production rate	(0.151, 0.510, 0.825)	(0.139, 0.482, 0.825)	(0.000, 0.217, 0.526)	(0.000, 0.235, 0.558)	(0.000, 0.235, 0.545)
Assay and blending	(0.000, 0.187, 0.520)	(0.000, 0.166, 0.520)	(0.000, 0.114, 0.403)	(0.000, 0.163, 0.491)	(0.000, 0.163, 0.491)
Breaking size of blasting	(0.000, 0.276, 0.655)	(0.000, 0.276, 0.655)	(0.000, 0.204, 0.538)	(0.000, 0.193, 0.538)	(0.000, 0.204, 0.538)
Rolling resistance	(0.000, 0.230, 0.562)	(0.000, 0.249, 0.595)	(0.000, 0.178, 0.518)	(0.000, 0.168, 0.518)	(0.000, 0.178, 0.518)
Bench height	(0.152, 0.508, 0.858)	(0.206, 0.619, 0.909)	(0.000, 0.385, 0.747)	(0.000, 0.269, 0.599)	(0.000, 0.309, 0.650)
Inflation factor	(0.000, 0.276, 0.655)	(0.000, 0.254, 0.619)	(0.000, 0.234, 0.570)	(0.000, 0.168, 0.497)	(0.000, 0.260, 0.655)
Ground condition	(0.067, 0.425, 0.909)	(0.045, 0.375, 0.909)	(0.000, 0.290, 0.730)	(0.067, 0.425, 0.909)	(0.198, 0.479, 0.909)
Weather condition	(0.000, 0.209, 0.655)	(0.000, 0.234, 0.655)	(0.000, 0.148, 0.541)	(0.000, 0.169, 0.541)	(0.000, 0.200, 0.596)
Moisture	(0.000, 0.247, 0.655)	(0.000, 0.247, 0.655)	(0.000, 0.135, 0.493)	(0.000, 0.162, 0.544)	(0.000, 0.135, 0.493)
Environment	(0.000, 0.238, 0.681)	(0.000, 0.225, 0.681)	(0.000, 0.000, 0.529)	(0.000, 0.000, 0.560)	(0.000, 0.219, 0.643)
Fill factor	(0.000, 0.267, 0.655)	(0.000, 0.267, 0.655)	(0.000, 0.147, 0.534)	(0.000, 0.179, 0.593)	(0.000, 0.147, 0.534)
Matching with truck	(0.038, 0.240, 0.681)	(0.038, 0.240, 0.681)	(0.000, 0.120, 0.454)	(0.076, 0.361, 0.681)	(0.076, 0.361, 0.681)
Flexibility	(0.000, 0.338, 0.761)	(0.083, 0.346, 0.825)	(0.000, 0.250, 0.641)	(0.078, 0.338, 0.779)	(0.000, 0.287, 0.678)
Operator skill	(0.128, 0.455, 0.825)	(0.112, 0.419, 0.779)	(0.000, 0.310, 0.641)	(0.112, 0.419, 0.779)	(0.139, 0.482, 0.825)
Maintenance	(0.021, 0.235, 0.682)	(0.031, 0.264, 0.682)	(0.000, 0.172, 0.619)	(0.021, 0.235, 0.682)	(0.028, 0.247, 0.750)
Utilization	(0.050, 0.373, 0.825)	(0.134, 0.572, 0.825)	(0.000, 0.280, 0.612)	(0.010, 0.296, 0.679)	(0.010, 0.296, 0.679)
Mobility	(0.000, 0.332, 0.719)	(0.000, 0.306, 0.678)	(0.000, 0.266, 0.641)	(0.112, 0.413, 0.825)	(0.000, 0.332, 0.719)
Availability	(0.076, 0.333, 0.750)	(0.071, 0.325, 0.708)	(0.000, 0.261, 0.616)	(0.071, 0.325, 0.708)	(0.000, 0.283, 0.653)
Continuous working	(0.062, 0.295, 0.708)	(0.082, 0.347, 0.794)	(0.062, 0.295, 0.708)	(0.050, 0.257, 0.668)	(0.000, 0.237, 0.616)
Working stability	(0.074, 0.319, 0.736)	(0.098, 0.375, 0.825)	(0.074, 0.319,0.736)	(0.059, 0.278, 0.695)	(0.000, 0.256, 0.641)
Useful life	(0.000, 0.249, 0.619)	(0.000, 0.303, 0.655)	(0.000, 0.296, 0.619)	(0.000, 0.212, 0.551)	(0.000, 0.170, 0.480)
Working space	(0.000, 0.233, 0.570)	(0.000, 0.284, 0.619)	(0.000, 0.262, 0.570)	(0.000, 0.326, 0.655)	(0.000, 0.345, 0.655)
Time cycle	(0.000, 0.264, 0.655)	(0.000, 0.314, 0.655)	(0.000, 0.238, 0.584)	(0.000, 0.196, 0.538)	(0.000, 0.180, 0.497)
Automation	(0.000, 0.253, 0.681)	(0.000, 0.301, 0.681)	(0.000, 0.000, 0.607)	(0.000, 0.233, 0.643)	(0.000, 0.198, 0.560)
Operating cost	(0.087,0.134,0.153)	(0.144,0.219,0.251)	(0.067,0.102,0.117)	(0.118,0.18,0.206)	(0.103,0.157,0.179)
Capital cost	(0,0.475,0.837)	(0,0.414,0.791)	(0,0,0.418)	(0,0.533,0.837)	(0.246,0.613,0.908)

The ideal fuzzy positive situation is $\tilde{v}_j^{+} = (1,1,1)$ and the ideal fuzzy negative situation is $\tilde{v}_j^{-} = (0,0,0)$. In the next stage, the proximity to the positive and negative ideals should be determined. As illustration, the distances from the positive and negative ideals for hydraulic shovel are:

$$d^{+}_{A1} = \sqrt{\frac{1}{3}\left[(1-0.151)^2+(1-0.51)^2+(1-0.825)^2\right]} + \sqrt{\frac{1}{3}\left[(1-0)^2+(1-0.187)^2+(1-0.52)^2\right]} + \sqrt{\frac{1}{3}\left[(1-0)^2+(1-0.276)^2+(1-0.655)^2\right]} + \ldots + \sqrt{\frac{1}{3}\left[(1-0.087)^2+(1-0.134)^2+(1-0.153)^2\right]} + \sqrt{\frac{1}{3}\left[(1-0)^2+(1-0.475)^2+(1-0.837)^2\right]} = 18.485 \qquad (19)$$

$$d^{-}_{A1}=\sqrt{\frac{1}{3}\left[(0-0.151)^2+(0-0.51)^2+(0-0.825)^2\right]}+\sqrt{\frac{1}{3}\left[(0-0)^2+(0-0.187)^2+(0-0.52)^2\right]}+\sqrt{\frac{1}{3}\left[(0-0)^2+(0-0.276)^2+(0-0.655)^2\right]}+\ldots+\sqrt{\frac{1}{3}\left[(0-0.087)^2+(0-0.134)^2+(0-0.153)^2\right]}+\sqrt{\frac{1}{3}\left[(0-0)^2+(0-0.475)^2+(0-0.837)^2\right]}=11.329 \quad (20)$$

Then the proximity to the ideal answer is calculated using the eq.16. Table 11 and fig. 6 show ranking of loading equipment from fuzzy TOPSIS.

Table 11

Ranking of loading equipment from Fuzzy TOPSIS method

	d_i^+	d_i^-	CL_i	Ranking
Hydraulic shovel	18.4852	11.32975	0.380002	2
Cable shovel	18.68885	11.63926	0.383778	1
Dragline	20.07162	9.105969	0.312088	5
Wheel loader	19.25507	10.2616	0.347655	3
Backhoe loader	19.56252	10.21698	0.343088	4

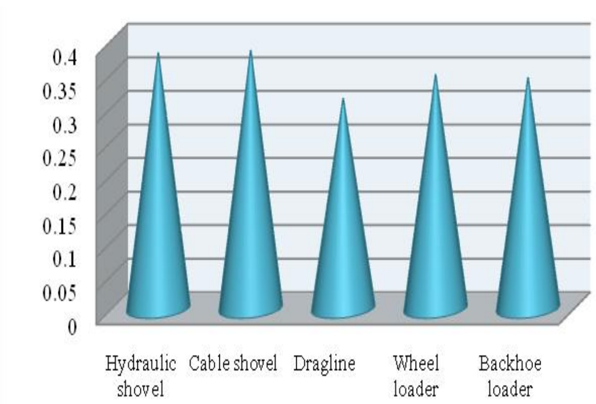

Figure 6. Final rank for loading equipment

In summary, cable shovel (A2) is the optimal loading equipment chosen from the five alternatives with the total performance value of 0.3838; while hydraulic shovel, wheel loader, backhoe loader and dragline achieving the subsequent rankings with the following respective scores 0.38, 0.3477, 0.3431 and 0.3121.

Conclusions

Based on the special characters of mining operations and high costs of equipment, it is really important to select the optimal equipment for loading and hauling. As there are many factors to consider which may not always be aligned, it is can be difficult and complex to decide the most suitable equipment. This article aimed at presenting the improved multi criteria decision making solution to loading equipment selection in open–pit mines. This problem is affected by uncertain and imprecise data; therefore, fuzzy–sets are useful for handling inherent uncertainties. In this paper, the hybrid method of fuzzy AHP, ANP and Fuzzy TOPSIS, is used for loading equipment selection in open–pit mines. The proposed model considers both qualitative and quantitative criteria as well as existing uncertainty, simultaneously and overcome the drawbacks of traditional equipment selection methods. By using this hybrid method, cable shovel and truck with the weight of 0.3838 were selected as the optimal alternative for the purpose of loading and hauling operation in Gole Gohar surface mine. Other loading equipment include hydraulic shovel, wheel loader, backhoe loader and dragline have achieved subsequent and less favorable rankings for this operating site. The proposed loading and hauling system for the mine caused significant decreases of equipment idle time and operating costs and with rather acceptable material transportation rate. This method is also applicable for selection of earth–moving machinery for other open–pit mining project, with required operational modifications.

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Įrangos pasirinkimas naudojant apytikslį daugiakriterį sprendimų modelį: „*Gole Gohar* geležies rūdos kasyklos“ pavyzdžiu

Santrauka

Krovimo ir gabenimo įrenginių pasirinkimas yra vienas svarbiausių etapų projektuojant paviršiaus kasyklas. Krovimo ir gabenimo darbai sudaro didžiąją dalį (65 proc.) visų išlaidų, esančių paviršinėse kasyklose, todėl labai svarbu pasirinkti tinkamą įrangą, nes tik taip galima gerokai sumažinti išlaidas. Norint pasirinkti tinkamą paviršiaus kasybos įrangą darbai atliekami trimis etapais. Pirma – nustatomi galimi įrangos tipai kasyklos eksploatavimo sąlygomis. Antra –parenkamos krovimo ir gabenimo įrangos atsižvelgiant į reikalingą kaušo talpą ir krovimo įrangos iškrovimo aukštį. Ir trečia – remiantis metinėmis produkcijos prognozėmis nustatoma kokio tipo mašinų ir kiek reikia norint atlikti darbus.

Įrangos pasirinkimas, kuris gali būti naudojamas pakrauti ir gabenti krovinius paviršiaus kasyklose , yra gan didelis. Norint pasirinkti geriausią įrangą, turėtų būti išanalizuoti visi galimi jos pasirinkimo variantai. Veiksnius, turinčius įtaką įrangos pasirinkimui galima būtų suskirstyti į keturias grupes: technines specifikacijas, veiklos efektyvumo, kapitalo ir veiklos sąnaudas. Kai kurie iš šių veiksnių yra kiekybiniai, o kiti – kokybiniai, (siekiant juos padaryti kiekybiniais, reikalinga matavimo metodika). Norint veiksmingai panaudoti šią įrangą, reikia nemažai žinių ir įgūdžių. Šie dalykai sukuria aplinką, kurioje sunku vienu metu analizuoti visus svarbius veiksnius.

Straipsnyje apžvelgtos skirtingos metodikos, kurios naudojamos pasirenkant paviršinės kasybos įrenginius, įskaitant, bet neapsiribojant ekspertinėmis sistemomis, matematiniu modeliavimu, kompiuteriniu modeliavimu, sekų teorija ir daugiakriteriniu vertinimu.

Nagrinėjami procesai nėra tinkamai apibrėžti, efektyvumo parametrai (kriterijai) dažnai prieštarauja vieni kitiems. Be to, tenka derinti kiekybinius ir kokybinius kriterijus. Dėl šių priežasčių pasirinkti tinkamą pakrovimo sistemą yra sudėtinga problema. Čia visiškai netinka tradiciniai, pasirinkimo pagal vieną kriterijų, metodai. Pagrindinis šio darbo uždavinys – pateikti apytikslį daugiatikslį (daugiakriterį) sprendimų modelį, taikomą nenumatytų, skirtingų tikslų atveju. Taikant šį metodą apytikslis AHP ir ANP (autorius T. L. Saaty) mišrus modelis buvo naudojamas siekiant nustatyti parametrų (kriterijų) svorius. AHP metodas yra plačiai naudojamas todėl, kad galima efektyviai suderinti kiekybinius ir kokybinius kriterijus. AHP ir *fuzzy* logikos kombinacija leidžia išspręsti esamus neaiškumus, nesuderinamumus ir problemas. Be to, naudojamas ANP, nes yra netiesiniai ryšiai tarp hierarchinių lygmenų, kas sudaro problemas įgyvendinant ANP metodą. Nustačius kriterijų svorius, pakrovimo ir transportavimo įranga *Gole Gohar* paviršiaus kasyboje buvo atrinkta naudojant TOPSIS metodą ir taikant *fuzzy* (apytikslę) aplinką. Modelis pasižymi racionalia struktūra, paprastumu, skaičiavimo efektyvumu ir gebėjimu nustatyti santykinio našumo galimybę paprasta matematine forma.

Pritaikyta *fuzzy* teorija sukurta 1965 m. L. A. Zadeh, o AHP metodas sukurtas 1980 m. T. L. Saaty. Pastaruoju metu, nagrinėjant ekonomikos ir inžinerines problemas, Saaty metodas tapo labai populiarus. Naudojantis šia metodika, asmenys, priimantys sprendimus, įvertinę turimas žinias, patirtį, prielaidas gali teikti pirmenybę savo tikslams. AHP suteikia struktūrizuotą pagrindą nustatant prioritetus kiekviename hierarchijos lygyje naudojant porinius palyginimus. Saaty taip pat pasiūlė ANP, apibendrindamas AHP (T. L. Saaty 1996). TOPSIS metodas paskelbtas Hwang ir Yoon (1981) yra jau seniai taikomas nagrinėjant technines problemas (E. K. Zavadskas 1987). Naudojant šią metodiką galima gauti rezultatus, kurie parodo, kada pasirinkta alternatyva turi mažiausią atstumą nuo geriausio racionalaus sprendimo (geriausia įmanoma būklė) ir didžiausią atstumą nuo neigiamo racionalaus sprendimo (blogiausias galimas sprendimas). TOPSIS metodas yra plačiai taikomas skirtingiems uždaviniams spręsti (Zavadskas ir Antuchevičienė 2006; Lin 2011; Liaudanskiene ir kt. 2009; Rudžianskaitė-Kvaraciejienė ir kt. 2010; Zavadskas ir kt. 2010b; Antucheviciene ir kt. 2010; Čokorilo ir kt. 2010; Lashgari ir kt. 2011; Tupenaitė ir kt. 2011; Han ir Lin 2011; Azimi ir kt. 2011).

TOPSIS neapibrėžta aplinka sukurta Chen (2000). Ji yra naudojama kaip patikima priemonė valdyti verbalinius ekspertų sprendimus ir pateikti galutinį veiklos rangą.

Anksčiau minėti metodai buvo sujungti į hibridinį sprendimų modelį, leidžiantį pasirinkti konkretų įrangos *Gole Gohar* geležies rūdos kasyklai pavyzdį. Siūlomas modelis įvertina tiek kokybinius, tiek kiekybinius kriterijus. Taip pat įvertinamas esamas neapibrėžtumas, taip pat įveikti trūkumai taikant tradicinius įrangos atrankos metodus. Naudojant hibridinį metodą, buvo pasirinkta optimali alternatyva krovimo ir gabenimo operacijoms *Gole Gohar* paviršiaus kasykloje taikant lyninį krautuvą ir sunkvežimius (rango reikšmė 0,3838). Kita krovimo įranga buvo hidraulinis kastuvas, frontalinis krautuvas, ekskavatorius-krautuvas. Draglainas turi mažesnius rangus, todėl ne toks tinkamas šiai užduočiai. Siūloma pakrovimo ir gabenimo sistema šiai kasyklai buvo tinkamiausia. Siūlomas hibridinis sprendimų metodas taip pat gali būti taikomas žemės darbų technikos atrankai kitų atvirų kasyklų projektams vertinti, prieš tai įvertinus kriterijus reikalingus tinkamai veiklai.

Raktažodžiai: *MCDM, Fuzzy Sets, AHP, ANP, TOPSIS, integruotas modelis, įranga, atrinkimas.*

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