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Arch. Min. Sci., Vol. 58 (2013), No 1, p. 255–267

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.2478/amsc-2013-0018

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EVALUATION OF WHEEL LOADERS IN OPEN PIT MARBLE QUARRYING BY USING THE AHP AND TOPSIS APPROACHES

OCENA PRACY ŁADOWARKI NA PODWOZIU KOŁOWYM W ODKRYWKOWEJ KOPALNI MARMURU W OPARCIU O METODY AHP I TOPSIS

The marble mining in Turkey has been rising since the early 80's. In relation to that, the marble income has become noticeably bigger than those of other mining sectors. In recent years, marble and natural stone export composes half of the total mine export with a value of two billion dollars. This rapid development observed in marble operation has increased the importance of mining economics, income-expenditure balance and cost analysis. The most important cost elements observed in marble quarrying are machinery and equipment, labor costs and geological structures of the field.

The aim of this study is to is to propose a multi-criteria decision making (MCDM) approach to evaluate the wheel loader alternatives and select the best loader under multiple criteria. A two-step methodology based on two MCDM methods, which are namely the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), are used in the evaluation procedure. More precisely, AHP is applied to determine the relative weights of evaluation criteria and TOPSIS is applied to rank the wheel loader alternatives. The proposed approach also provides a relatively simple and very well suited decision making tool for this type of decision making problems.

Keywords: Wheel loader selection, AHP, TOPSIS, Multiple Criteria Decision Making

Wydobycie marmuru w Turcji systematycznie wzrasta od początku lat 80-tych XX wieku a zyski ze sprzedaży marmuru są większe niż te, notowane w innych gałęziach sektora wydobywczego. W ostatnich latach eksport marmuru i kamieni naturalnych osiągnął poziom 50 % całego eksportu z sektora wydobywczego, a jego wartość osiągnęła dwa miliardy dolarów. Ten gwałtowny wzrost wydobycia marmuru postawił w centrum uwagi takie zagadnienia jak ekonomia projektu, bilansowanie wydatków i dochodów oraz analizy kosztów. Najważniejszymi kosztami ponoszonymi w związku z prowadzeniem wydobycia marmuru w kamieniołomach to koszty maszyn i urządzeń, koszty robocizny oraz koszty związane ze strukturą geologiczną pola.

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Celem obecnej pracy jest zaproponowanie nowego podejścia wspierającego wielokryterialne procesy decyzyjne i wykorzystanie go do oceny rozwiązań alternatywnych dla zastosowania ładowarki na podwoziu kołowym i do wyboru optymalnej ładowarki. Procedura oceny wykorzystuje dwu-stopniową metodologię opartą na dwóch metodach decyzyjnych: metoda AHP (Analytic Hierarchy Process) oraz metodę TOPSIS (Technique for Order Preference by Similarity to Ideal Solutions- technika preferencji kolejności w oparciu o podobieństwo do rozwiązań idealnych). Metoda AHP została zastosowana dla określenia relatywnych wag poszczególnych kryteriów oceny, zaś metoda TOPSIS służyła do ustalenia kolejności i rangi poszczególnych rozwiązań alternatywnych (ładowarek). Zaproponowane podejście stanowi stosunkowo łatwe do zastosowania i odpowiednie do sytuacji narzędzie wspomagające procesy decyzyjne.

Słowa kluczowe: wybór ładowarki, AHP, TOPSIS, wielokryterialne procesy decyzyjne

1. Introduction

Turkey is one of the leading countries in limestone, marble, travertine and onyx reserves. Having approximately 40% of carbonate-based marble reserves of the entire world, Turkey is on the way to become the largest marble exporter. According to 2010 data, Turkey has exported 5,036,210 tons of marble blocks in return of 776 million US$ and 1,604,697 tons of finished marble products in return of 793 million US$.

Due to the growing demand for production in marble mining, the use of loaders and transporters with high capacity has become necessary. Accoding to Surttill (1988) states that the use of technologically equipped, bigger and faster machinery is more favorable to reduce the unit cost. On the other hand, (Mallı et al.,2 010) asserts that the best machine should be selected for each working environment considering relevant criteria instead of buying big and powerful machines that cause increasingly larger capital and finance difficulties. For this reason, nowadays the decision makers take advantage of a variant of MCDM methods (AHP, TOPSIS, PROMETHEE, etc.) to make the most suitable or beneficial decision on machine and equipment selection.

A review of the literature reveals that MCDM techniques have been used for a variety of specific applications in decision making problems in mining operations. Some major decisions that have to be made during mining operations are: selection of the production method, selection of machinery and equipment, location of the plant, planning of the quarry and pit, selection of service equipment, etc.

Karadogan et al. proposed a fuzzy attribute decision making (FADM) procedure for the selection of underground mining method. Samanta et al. incorporated the AHP method to the selection of open cast mining equipment. Kesimal and Bascetin also used the AHP method for machinery and equipment selection in mining. Bitarafan and Ataei solved the underground mining method selection problem using FADM. Kazakidis et al. showed the application of AHP for a series of case studies in different mining scenarios such as drilling technology, investment analysis, ground support design, tunneling systems' design, shaft location selection, mine-planning risk assessment (Karadogan et al., 2001; Samanta et al., 2002; Kesimal & Bascetin, 1999; Bitarafan & Ataei, 2004; Kazakidis et al., 2004). Elevli and Demirci also used PROMETHEE technique to decide on an underground transport system in a chrome mine. Also, the AHP process was developed for a location evaluation hierarchy of alumina cement plants in East-Azerbaijan province of Iran by Ataei. Yavuz and Alpay investigated the underground mining technique selection by multi-criteria optimization methods and Yavuz et.al. used the AHP method for the optimum support design selection of the main haulage road in WLC Tuncbilek colliery (Elevli & Demirci, 2004; Ataei, 2005; Yavuz & Alpay, 2010; Yavuz et al., 2008). Jamshidi et al., emphasized that for selecting a mining method, the AHP model is unique in its identification of multiple attributes, minimal data requirement and minimal time consumption while Aghajani and Osanloo had used the application of AHP-TOPSIS method for loading- haulage equipment selection in open pit mines (Jamshidi et al., 2009; Aghajani & Osanloo, 2007).

In Turkey at the present time, approximately 20,000 wheel loaders are used in the mining sector. Considering that marble quarrying comprises about half of the country's mining operations, it is apparent that most of them are functioning in the marble sector. While these machines are used in the removal of overburden, road planning, transportation and loading of marble blocks, and removal of waste material, they constitute one of the most important machines in the whole fleet of marble mining. That is why the wheel loader selection problem has become remarkably important. This selection problem can be viewed as a complex MCDM problem due to the availability of quantitative, qualitative, and multiple criteria that have to be considered in the decision process. This paper paper proposes a two-step MCDM approach based on the AHP and TOPSIS methods to assist the decision makers in selecting the best wheel loader in marble mining.

2. Proposed two-step AHP and TOPSIS methodolgy

The purpose of this paper is to develop a two-step approach that employs AHP and TOPSIS methodologies sequentially for selecting the best wheel loader machine. The proposed approach helps to decompose this unstructured problem into a reliable hierarchical structure that includes various criteria, sub-criteria, and alternatives. It starts with applying the AHP method to find the relative importance weights of the evaluation criteria in the decision hierarchy. Then, TOPSIS method uses these weights for determining the overall ranking scores of the machines. In the proposed methodology, the TOPSIS approach is used to achieve the final ranking of the wheel loaders. The evaluation procedure consists of the following three main steps:

Step 1. Identify the wheel loader evaluation criteria that are considered to be the most important.

Step 2. Build criteria hierarchy and determine the criteria weights with the AHP method.

Step 3. Use the TOPSIS method to establish a ranking of potential machines.

2.1. AHP Method

The Analytical Hierarchy Process (AHP) developed by Saaty (1980) is probably the best-known and most widely used model in decision making. AHP is a powerful decision making methodology to determine the priorities among different criteria. Three features of AHP, differentiate it from other decision making approaches: (i) its ability to handling both tangible and intangible attributes, (ii) its ability to structuring the problems, in a hierarchical manner to gain insights into the decision making process, and (iii) its ability to monitoring the consistency with which a decision maker uses his/her judgment (Jamshidi et al., 2009).

It quantifies decision-makers' subjective judgments by assigning corresponding numerical values based on the relative importance of the criteria under consideration. The magnitude of importance between the criteria is determined by using pairwise comparisons. In a pairwise comparison, the decision maker compares two criteria and indicates an importance degree by using the standard scale given in Table 1. Once all the criteria are compared pairwise, the whole pairwise comparisons are collected in a matrix called a pairwise comparison matrix.

TABLE 1

Importance scale for pairwise comparisons by Saaty and Alexander (1981)

Importance Level	Numerical Value
Equally important	1
Moderately more important	3
Strongly more important	5
Very strongly important	7
Extremely more important	9
2,4,6,8	Intermediate values of importance

The AHP encompasses five basic steps to determine the priorities among the evaluation criteria as shown below:

Step 1. Determine the hierarchical structure of evaluation criteria.

Step 2. Construct pairwise comparison matrices (P) among the main criteria and the sub-criteria with respect to their corresponding main criteria using the importance scale given in Table 1. A criteria compared with itself is always assigned the value "1" so the main diagonal entries of the pairwise comparison matrix are all "1". Each row and column of this matrix is allocated to one criterion and it can be described as:

$$A = \begin{matrix} \\ C_1 \\ C_2 \\ C_3 \\ \vdots \\ C_n \end{matrix} \begin{matrix} \begin{matrix} C_1 & C_2 & C_3 & \cdots & C_n \end{matrix} \\ \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & 1 & a_{23} & \cdots & a_{2n} \\ a_{31} & a_{32} & 1 & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & \cdots & 1 \end{bmatrix} \end{matrix} \tag{1}$$

where a_{ij} is the relative importance of criterion C_i with respect to criterion C_j. In the matrix,

$$a_{ij} = 1 \quad \text{when} \quad i = j \quad \text{and} \quad a_{ij} = 1/a_{ij} \tag{2}$$

Step 3. Normalize the pairwise comparison matrices and calculate the priorities of each matrix. For this purpose, each set of column values is summed. Then, each value is divided by its respective column total value. Finally, the average of rows is calculated and the relative weights of criteria are obtained, where $W = [w_1 \quad w_2 \quad \ldots \quad w_n]$ is the criteria weight vector and

$$\sum_{i=1}^{n} w_i = 1 \tag{3}$$

Step 4. Do consistency checks for all the pairwise comparison matrices to ensure that they are reasonable and acceptable. Let C denote an n-dimensional column vector describing the sum of the weighted values for the importance degrees of criteria, then

$$C = [c_i]_{nx1} = A\,.\,WT, \quad i = 1, 2, \ldots, n \tag{4}$$

where

$$A.W^T = \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & 1 & a_{23} & \cdots & a_{2n} \\ a_{31} & a_{32} & 1 & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & \cdots & 1 \end{bmatrix} \cdot \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ \vdots \\ c_n \end{bmatrix} \tag{5}$$

The consistency values can be represented by the vector $CV = [cv_i]_{1xn}$ for each criterion in the comparison matrix with cv_i defined as:

$$cv_i = \frac{c_i}{w_i}, \qquad i = 1, 2, ..., n \tag{6}$$

The relative weights represent the eigenvalues of each criterion and $\lambda_{\max}$ gives the highest eigenvalue which is calculated as:

$$\lambda_{\max} = \frac{\sum_{i=1}^{n} cv_i}{n}, \qquad i = 1, 2, ..., n \tag{7}$$

With the maximal eigenvalue $\lambda_{\max}$, a consistency index (CI) can then be determined by Saaty (1981):

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{8}$$

Finally, the consistency ratio (CR) is calculated as:

$$CR = \frac{CI}{RI} \tag{9}$$

where RI denotes the average random index with the value obtained by different orders of the pairwise comparison matrices. This ratio should be lower than 0.1 to consider the judgments consistent and acceptable so that the derived weights can be used by Saaty (1980). If this is not the case, the decision-maker should go back to Steps 2 and 3 and redo the assessments and comparisons.

Step 5. Finally, the global weights are obtained by multiplying the local weight of each sub-criterion with the local weight of its respective main criterion. The calculated global weights will be used in the determination of the overall ranking scores of the machines by the TOPSIS method.

2.2. TOPSIS Method

TOPSIS which is one of the well-known multi-criteria decision making methods is presented in Chen & Hwang (1992), with reference to Hwang & Yoon (1981). TOPSIS is a viable method for the proposed problem and is suitable for the use of precise performance ratings. When the performance ratings are vague and inaccurate, then the fuzzy TOPSIS is the preferred technique (Aghajani et al, 2009). It is a practical and useful technique for ranking and selecting a number of externally determined alternatives through distance measures. It is based upon the concept that the chosen alternative should have the shortest distance from the positive ideal solution (PIS) and the farthest from the negative ideal solution (NIS). The PIS is the solution that maximizes the benefit and also minimizes the total cost. On the contrary, the NIS is the solution that minimizes the benefit and also maximizes the total cost. TOPSIS simultaneously considers the distances to both PIS and NIS. At the end, the ideal solution closest to the PIS and farthest to NIS is obtained.

In this study, the final ranking of wheel loader alternatives is determined by the TOPSIS method. Once the global weights of criteria are calculated using the AHP approach, they are incorporated into the decision matrix that contains the performance values of machine alternatives with respect to each related criteria. In the following, the computational steps of TOPSIS are given:

Step 1. Once the decision matrix is formed, the normalized decision matrix is calculated as:

$$r_{ij} = \frac{y_{ij}}{\sqrt{\sum_{j=1}^{J} y_{ij}^2}}, \qquad i = 1, \ldots, n; \quad j = 1, \ldots, J \tag{10}$$

where y_{ij} is the performance value of machine j against criterion i.

Step 2. The weighted normalized decision matrix is obtained by multiplying the normalized decision matrix with the weights of the criteria:

$$v_{ij} = w_i \times r_{ij}, \qquad i = 1, \ldots, n; \quad j = 1, \ldots, J \tag{11}$$

where w_i is the weight of the i-th criterion and $\sum_{i=1}^{n} w_i = 1$.

Step 3. In this step, the negative and positive ideal solutions are determined. The ideal solution, $A^*(v_i^*,\ i = 1, \ldots, n)$, is made of all the best performance scores and the negative ideal solution, $A^-(v_i^-,\ i = 1, \ldots, n)$, is made of all the worst performance scores for the criteria in the weighted normalized decision matrix. They are calculated using equations 13 and 14.

$$A^* = \{v_1^*, v_2^*, \ldots, v_n^*\} = \{(max_j v_{ij} | i \in I'), (min_j v_{ij} | i \in I'')\} \tag{12}$$

$$A^- = \{v_1^-, v_2^-, \ldots, v_n^-\} = \{(min_j v_{ij} | i \in I'), (max_j v_{ij} | i \in I'')\} \tag{13}$$

In these equations, the criteria are divided into two classes: the first class is of an input or cost nature, denoted by the set I', and smaller performance scores for these criteria are preferred; the second class is of an output or benefit nature, denoted by the set I'' and larger performance scores for these measures are preferred.

Step 4. The distance of each alternative from PIS and NIS is calculated using the *n*-dimensional Euclidean distance as follows:

$$D_j^* = \sqrt{\sum_{i=1}^{n} \left(v_{ij} - v_i^*\right)^2}, \qquad j = 1, 2, \ldots, J \tag{14}$$

$$D_j^- = \sqrt{\sum_{i=1}^{n} \left(v_{ij} - v_i^-\right)^2}, \qquad j = 1, 2, \ldots, J \tag{15}$$

Step 5. The next step consists of the calculation of the relative closeness to the ideal solution. The relative closeness of the alternative a_j with respect to A^* is defined as:

$$C_j^* = \frac{D_j^-}{D_j^* + D_j^-}, \qquad j = 1, 2, \ldots, J \tag{16}$$

Step 6. Rank the preference order in the decreasing order of C_j^* values.

In the TOPSIS method, the chosen alternative has the maximum value of C_j^* with the intention to minimize the distance from the positive ideal solution and to maximize the distance from the negative ideal solution.

3. Wheel loader evaluation framework

Based on the investigation of wheel loaders, nine alternatives (A_1, A_2, ..., A_9) have been specified as preferable in marble mining. Economic, technical, operational, and commercial criteria (C_1, C_2, C_3, C_4) are defined as main criteria in this study. Each of these main criteria is divided into sub-criteria (C_{11}, C_{12}, …,C_{42}). For instance, the operation criterion is divided into sub-criteria as block size and operational capacity. The proposed evaluation procedure for selecting the best wheel loader is given in Figure 1.

The hierarchy design of the evaluation procedure is illustrated in Figure 2 with the main and sub-criteria definitions and their symbolic notations.

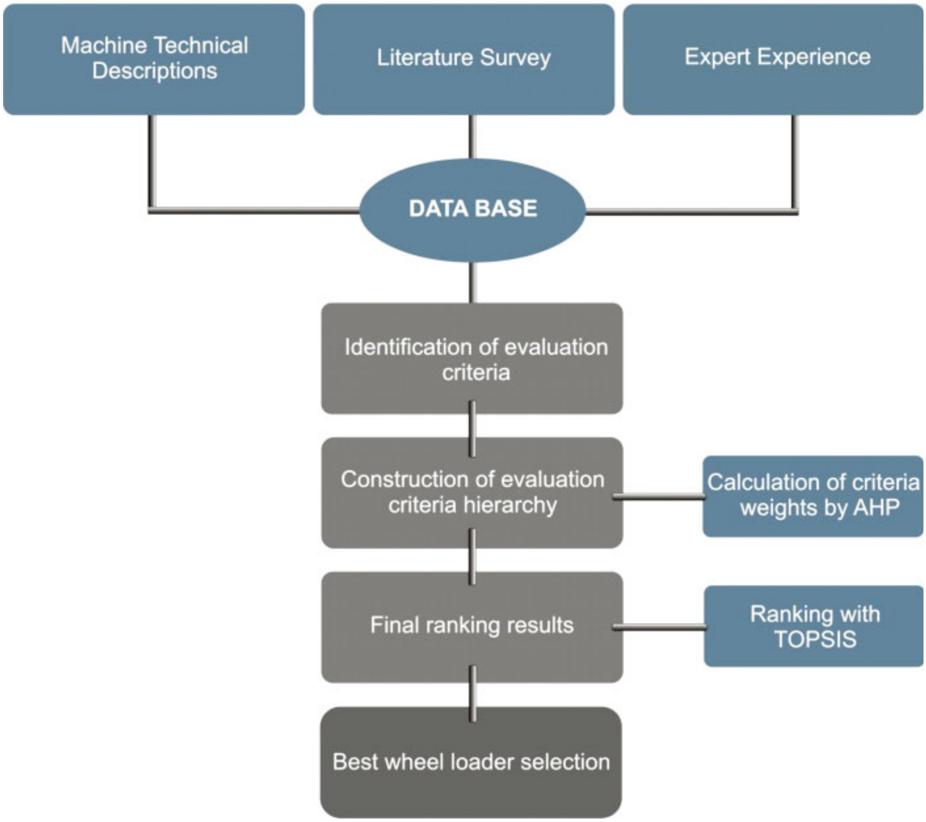
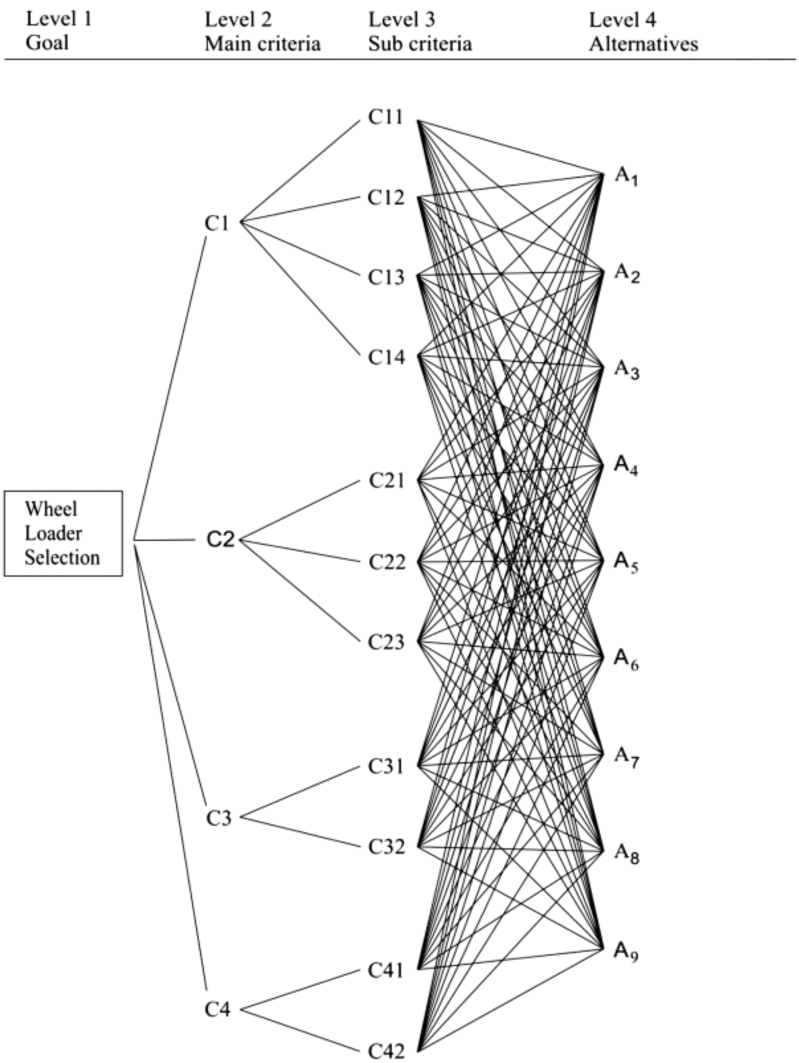


Fig. 1. The framework of the proposed evaluation procedure

3.1. Application of the AHP approach in calculating the weights of the criteria

Initially, the local weights of the main criteria are determined by constructing the pairwise and normalized pairwise comparison matrices. The pairwise comparison matrice (P) is given in Table 3. To calculate the relative importance values of the main criteria, the elements of each column of the P matrix are divided by the sum of that column (i.e. normalizing the column), which are shown in Table 4. The elements of the normalized row are added (to obtain 'a row sum') and then divided by three (the number of components being compared) to obtain the local weights of the main criteria in the last column of Table 4.

The local weights of the sub-criteria are calculated in the same manner using the AHP approach. Subsequently, the global weights of the sub-criteria are calculated by multiplying the local weight of each sub-criterion with the local weight of its respective main criteria given in Table 4. The local weights of the main and sub-criteria are provided in the first and second columns of Table 5. The global weights of the sub-criteria with respect to the main criteria are also provided in the third column.



Main criteria	Notation	Sub criteria	Notation
Economic	C_1	Investment	C_{11}
		Fuel expense	C_{12}
		Spare parts	C_{13}
		Second-hand value	C_{14}
Technical	C_2	Gross power	C_{21}
		Operating weight	C_{22}
		Economical life	C_{23}
Operation	C_3	Block size	C_{31}
		Operational capacity	C_{32}
Commercial	C_4	Terms of service	C_{41}
		Warranty terms	C_{42}

Fig. 2. The hierarchical structure of the wheel loader selection problem

TABLE 3

The pairwise comparision matrix of the main criteria

	Economic features	**Technical features**	**Operational features**	**Commercial features**
Economic features	1	3	2	5
Technical features	1/3	1	2	3
Operational features	1/2	1/2	1	5
Commercial features	1/5	1/3	1/5	1
Column sum	2.03	4.83	5.20	14.00

TABLE 4

Normalized pairwise comparision matrix of the main criteria

	Economic features	**Technical features**	**Operational features**	**Commercial features**	**Local Weights**
Economic features	0.49	0.62	0.38	0.36	0.46
Technical features	0.16	0.21	0.38	0.21	0.24
Operational features	0.25	0.10	0.19	0.36	0.23
Commercial features	0.10	0.07	0.04	0.07	0.07

$\lambda_{\max} = 4.2249; \quad CI = 0.0749; \quad RI = 0.9; \quad CR = 0.083 \leq 0.1$

TABLE 5

Weights of the evaluation criteria

Criteria	**Local weight of main criteria**	**Local weight of sub-criteria**	**Global weight of sub-criteria**	**Ranking**
Economic	0.464			
Investment		0.42	0.193	1
Fuel consumption		0.33	0.154	2
Spare parts		0.16	0.072	8
Second-hand value		0.10	0.045	9
Technical	0.242			
Engine power		0.36	0.087	5
Operating weight		0.33	0.081	6
Economical life		0.31	0.075	7
Operational	0.225			
Block size		0.56	0.125	3
Operational capacity		0.44	0.100	4
Commercial	0.069			
Serviceability		0.60	0.042	10
Warranty terms		0.40	0.028	11

3.2. Application of the TOPSIS approach to obtain ranking of the wheel loaders

As the first step of TOPSIS method, the performance values of the machines with respect to the evaluation criteria are collected and the decision matrix is constructed using the data given in Table 6. These data can be either quantified performance such as motor power and fuel cost or qualified performance such as economic life and after sale service. Qualified performance is a score which is determined subjectively by the experts ranging from 1 to 5 points and the higher the score the better is the performance. TOPSIS will then use the global weights of criteria obtained by the AHP method and the decision matrix in the computations and the remaining steps of the methodology will be applied as follows:

- The performance data of the machines given in Table 6 is normalized using equation 10 as explained in section 2.2. And the weighted normalized decision matrix is calculated by multiplying the normalized decision matrix with the global weights using equation 11.
- The positive ideal and negative ideal solutions are obtained using equation 12 and 13.
- The computed distances of each alternative to positive ideal and negative ideal solutions are obtained using equations 14 and 15, respectively and given in Table 7.
- The relative closeness of a particular alternative to the ideal solution is calculated using equation 16 and shown in Table 8.
- The alternatives are arranged in descending order according to their relative closeness value and the final ranking of the alternatives are shown in Table 8.

TABLE 6

Decision matrix (Performance data of nine wheel loaders)

Criteria	Unit	Polarity	Alternatives								
			A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
C_{11}	(€)	–	260000	220000	205000	245000	280000	200000	280000	220000	270000
C_{12}	(lt/h)	–	30	24	22	22	28	18	32	20	24
C_{13}	5 scales	+	4	4	4	4	4	1	2	3	3
C_{14}	(€)	+	86000	73000	68000	82000	93000	67000	93000	73000	90000
C_{21}	(hp)	+	322	287	260	303	352	216	380	261	315
C_{22}	(kg)	+	33300	25148	23698	29000	33000	14472	34000	21905	28960
C_{23}	5 scales	+	5	4	3	4	5	2	4	3	5
C_{31}	5 scales	+	5	4	3	4	5	2	5	3	4
C_{32}	5 scales	+	5	4	3	4	5	2	5	3	5
C_{41}	5 scales	+	5	5	4	5	5	3	4	4	4
C_{42}	5 scales	+	5	5	4	5	5	3	4	4	4

Polarity: ‘+’ = benefit criteria, ‘–’ = cost criteria.

TABLE 7

The distances of each alternative to the PIS and NIS

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
D_j^*	0.030	0.024	0.034	0.022	0.030	0.055	0.039	0.035	0.027
D_j^-	0.054	0.045	0.040	0.046	0.055	0.036	0.049	0.037	0.046

TABLE 8

The relative closeness and rank of alternatives

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
C_j^*	0.642	0.656	0.537	0.674	0.648	0.394	0.555	0.513	0.633
Rank	4	2	7	1	3	9	6	8	5

Finally, the wheel loader A_4 is chosen as the best alternative with the with the highest C_j^* value of 0.674.

5. Conclusion

In this paper, the evaluation of loading machines under multiple criteria is handled by a two-step AHP and TOPSIS methodology. This approach eliminates the weaknesses of AHP and TOPSIS in stand-alone utilization, and provides a relatively simple and very well suited decision-making tool for selecting the best wheel loader. The proposed approach helps to decompose this unstructured problem into a reliable hierarchical structure that includes various criteria, sub-criteria, and alternatives. It starts with applying the AHP method to find the relative importance weights of the evaluation criteria in the decision hierarchy. Then, TOPSIS method uses these weights for determining the overall ranking scores of the machines.

The most common wheel loader alternatives used in marble mining have been evaluated using the proposed approach. . The highest relative closeness values (C_j^*) have been obtained for A_4, A_2 and A_5 wheel loaders in order. The marble mining related assessments showed that the use of loaders with capacity of approximately 25-30 tons is more preferable to using more powerful and/or more economical loaders in regard to the capital cost. The best loader alternative chosen, A_4, is relatively preferable due to its higher operating weight and less fuel consumption compared to the other alternatives with better evaluations such as less investment.

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Received: 02 May 2012