Routledge
Taylor & Francis Group

Edinburgh Napier UNIVERSITY

INTERNATIONAL JOURNAL OF STRATEGIC PROPERTY MANAGEMENT
ISSN 1648-715X print / ISSN 1648-9179 online

2012 Volume 16(1): 85–104
doi:10.3846/1648715X.2012.666657

MAINTENANCE STRATEGY SELECTION USING AHP AND COPRAS UNDER FUZZY ENVIRONMENT

Mohammad Majid FOULADGAR [1], Abdolreza YAZDANI-CHAMZINI [2], Ali LASHGARI [3], Edmundas Kazimieras ZAVADSKAS [4] and Zenonas TURSKIS [5] ✉

[1] *Fateh Research Group Tehran, Department of Strategic Management, Milad building (No. 2), Mini City Aghdasieh, Tehran, Iran*
E-mail: manager@fatehidea.com
[2] *Fateh Research Group Tehran, Department of Strategic Management, Milad building (No. 2), Mini City Aghdasieh, Tehran, Iran*
E-mail: a.yazdani@fatehidea.com
[3] *Fateh Research Group Tehran, Department of Strategic Management, Milad building (No. 2), Mini City Aghdasieh, Tehran, Iran*
E-mail: a.lashgari@fatehidea.com
[4] *Research Institute of Internet and Intelligent Technologies, Vilnius Gediminas Technical University, Sauletekio al. 11 , LT-10223 Vilnius, Lithuania*
E-mail: edmundas.zavadskas@vgtu.lt
[5] *Department of Construction Technology and Management, Faculty of Civil Engineering, Vilnius Gediminas Technical University, Sauletekio al. 11 , LT-10223 Vilnius, Lithuania*
E-mail: zenonas.turskis@vgtu.lt

Received 18 July 2011; accepted 29 September 2011

ABSTRACT. Asset management, as a systematic process of operating, maintaining, and upgrading physical assets, is an important element of decision-making in heavy equipment management and operation. Maintenance strategy selection plays a significant role in mining design. However, the nature of maintenance strategy selection is a complex multi-criteria decision making (MCDM) problem including both tangible and intangible parameters which are often in conflicting with each other. As well as when decision makers are uncertain in determining and defining the ratings and the weights of alternatives and criteria respectively, fuzzy theory provides an appropriate tool to handle the existing uncertainties. In this paper, a new fuzzy MCDM method based on the concepts of COPRAS (COmplex PRoportional ASsessment) and AHP (Analytical Hierarchy Process) was proposed to evaluate the feasible maintenance strategy. The linguistic terms are employed to assess the ratings and weights. Fuzzy AHP is utilized to calculate the weights of the evaluation criteria; then, the rankings of alternatives are computed based on fuzzy sets theory and COPRAS. A real world case study is presented to illustrate a potential application of the proposed model.

KEYWORDS: COPRAS; AHP; Fuzzy set theory; Selection; Maintenance strategy

1. INTRODUCTION

In asset intensive industries such as mining and earthmoving operations, the productivity and reliability of capital assets is vital to financial success of projects. Maintenance operations can dramatically affect useful life and overall performance of an asset. Accordingly, both asset operators/owners and asset service providers are continually trying to improve their maintenance practices to select the most effective strategy for this important operation. Nowadays, billions of dollars are spent annually to produce different types of heavy machineries for use by construction and mining industries (Bashiri et al., 2011; Sayadi et al., 2012). The competitive global economy is forcing equipment managers to find optimum ways for increasing their competitiveness to contend against the other companies in the global marketplace, by improving their performance in terms of quality, flexibility, delivery time and cost. On the other hand, the safety related issues come under increased concentration which makes costs ineffective to have backup units (Dhillon, 2008). For this reason heavy equipment are becoming much more sophisticated and their capital and operational costs are increasing at an alarming rate. Heavy equipment managers need to optimize all effective parameters in order to meet production targets. There are various problems which can affect equipment performance; such as equipment fleet selection, scheduling and maintenance strategy selection.

Equipment maintenance cost is one of the main expenditure items for earthmoving operations which can reach up to 60% of operational costs (Sayadi et al., 2010), varying according machine type, working and environmental condition, maintenance level and strategy, etc (Nichols, 1976). Selection of optimum maintenance strategy plays an undeniable role in achieving organizational objectives as well as increasing productivity, reducing equipment downtime, minimizing overall cost and providing reliable machinery (Jafari et al., 2008). A survey of effectiveness of maintenance management in U.S. industries signifies that one third of overall maintenance costs are misspent as the result of unsuitably or unnecessary maintenance activities; so that, an annual loss of more than $60 billion is result of ineffective maintenance planning and management (Mobley, 2002).

There are a large number of tangible and intangible criteria, which often are in conflict with each other, that should be considered in selection of the best maintenance strategy. For these reasons, it is particularly difficult to equipment managers choose the best maintenance strategy for each piece of equipment from a set of feasible alternatives, especially during the feasibility studies and plant design stages. As a result, using multi attribute decision making methods can be useful.

In view of the fact that choosing of the most suitable maintenance strategy for different equipment is a crucial decision for managers, a large number of studies have been devoted to this field of research. In the literature, Murthy and Asgharizadeh (1999) recommended a methodology based on game theory for selection of maintenance strategy for the companies which outsource the maintenance operations. Almeida and Bohoris (1995) discussed a brief review of different decision theory concepts along with their applicability in the choosing of the most appropriate maintenance strategy. Bevilacqua and Braglia (2000) proposed a multi criteria decision making (MCDM) method based on analytic hierarchy process (AHP). In this research sufficient attributes have been considered in the form of a crisp MCDM method. Bertolini and Bevilacqua (2006) selected maintenance strategy for a set of centrifugal pumps used in an Italian oil refinery by using a hybrid method of goal programming and AHP. Al-Najjar and Alsyouf (2003) proposed a combination of fuzzy Inference System (FIS) and simple additive weighting (SAW), with considering a few failure causes as attributes, to make the optimum decision about maintenance strategy. Azadivar and Shu (1999) proposed a new method considering 16 different characteristic parameters as criteria for each class of systems in a just-in-time environment. Gaonkar et al. (2008) and Wang et al. (2007) present a fuzzy AHP approach to model the uncertainty in the choosing process of the optimum maintenance strategy.

Although there are a number of research works on maintenance strategy selection, there is still a need to use a systematic mathematical approach to help the decision maker in taking an appropriate decision for selecting the maintenance strategy. COPRAS, introduced by Zavadskas and Kaklauskas (1996), is a appropriate tool that its applicability and capability is demonstrated by different researchers (Kaklauskas et al., 2006, 2010, 2011; Zavadskas et al., 2009a, 2009b, 2010; Tupenaite et al., 2010; Uzsilaityte and Martinaitis, 2010; Madhuri et al., 2010; Chatterjee et al., 2011; Podvezko, 2011; Zavadskas and Turskis, 2011). This technique is able to determine a solution with the ratio to the ideal solution.

In this paper, we propose an integrated approach based on fuzzy AHP and COPRAS to solve MCDM problems in which the weights of criteria and the performance ratings of alternatives are calculated based on linguistics terms. The relative importance of criteria was calculated by Fuzzy AHP. The COPRAS technique was employed in order to evaluate the maintenance strategies. Finally, alternatives are ranked and the best one is selected.

The rest of the paper is organized as follows. In the next section, possible alternative maintenance strategies are summarized. In section 3, the fuzzy AHP methodology is briefly introduced, including fuzzy logic, fuzzy number, linguistic variables, and fuzzy AHP. In Section 4, the COPRAS approach is illustrated and described. The proposed method to solve MCDM problem is described in Section 5. Section 6 presents a real world case study to show the potential application of the proposed model to select an optimal strategy for maintenance. The implementation of proposed model is presented in section 7. Finally, the results are discussed in Section 8.

2. POSSIBLE ALTERNATIVE MAINTENANCE STRATEGIES

Five alternative maintenance strategies considered in this paper are briefly introduced as following: Failure based maintenance (FBM) is intended to repair a failed system. This maintenance is carried out after a failure. This means that the equipment will run until a breakdown occurs (Savsar, 2011). In some literature this is referred as fire-fighting maintenance, corrective maintenance or breakdown maintenance (Swanson, 2001).

Preventive maintenance (PM) is based on component reliability characteristic and intended to decrease the probability of the potential failures. This method is carried out at predetermined intervals or according to prescribed criteria (Moghaddam and Usher, 2011). Preventive maintenance is performed before machine failure in order to keep equipment in specified condition by providing organized check up, recognition, and prevention of potential failure (Mann et al., 1995). This means that preventive maintenance strategy is helpful in overcoming the difficulties associated with the wearing of elements (Tatari and Skibniewski, 2006).

Condition based maintenance (CBM) is based on the performance and monitoring of units from the system. The condition monitoring may be continuous or scheduled, on request. The gathered machine data from monitoring system can specify essential maintenance before forecasted failure. Maintenance program is implemented when a condition factor approaches or exceeds a threshold level. CBM is introduced as the most cost-effective means of maintaining critical equipment (Veldman et al., 2011; Andrawus, 2008).

Scheduled maintenance (SM) means that maintenance activities are implicated after an established time schedule, no matter the failure occurs or not. SM can be classified into age-based and clock-based maintenance, according to the time that a certain machine age is reached and a particular calendar time, respectively (Ahmadi et al., 2010). In some literature this strategy is referred to as time-based maintenance (Christer and Lee, 2000).

Opportunistic maintenance (OM) is an attempt to combine PM and FBM. The approach is to consider the failure of a unit as an opportunity to perform PM on other units and restore yet non-failed components in order to prevent future failures (Laggoune et al., 2009). Instead of scheduling the PM beforehand, a strategy is used that decides which PM carries out at a given state of the equipment (Khazraei and Deuse, 2011).

3. FUZZY AHP

Fuzzy set theory

Fuzzy set first proposed by Zadeh (1965), to model the existing uncertainty and the outputs be more precise, accurate, and reliable (Zadeh, 1975a, b, c). This powerful mathematical tool can provide the flexibility and robustness needed for the decision maker to understand the decision problem (Büyüközkan et al., 2011). These capability and efficiency of the method developed would facilitate its use in real world situations for making more effective decisions. A fuzzy set is a general form of a crisp set. Crisp sets only allow full membership or non-membership, whereas fuzzy sets allow partial memberships (Torlak et al., 2011). The MCDM problem has been tackled by various researchers working in the area of decision-making in a fuzzy environment (Gaonkar et al., 2008). A fuzzy set is defined between interval [0, 1], which 0 expresses do not belong to the set under consideration and 1 addresses full belong to the set.

As depicted in Figure 1, a fuzzy number $\tilde{A}$ on real numbers R is a triangular fuzzy number (TFN), if its membership function $\mu_{\tilde{A}}(x)$ be as follows:

$$\mu_{\tilde{A}}(x) = \begin{cases} (x-l)/(m-l), & l \le x \le m, \\ (u-x)/(u-m), & m \le x \le u, \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where: $-\infty < l \le m \le u < +\infty$ and can be shown as (l, m, u).

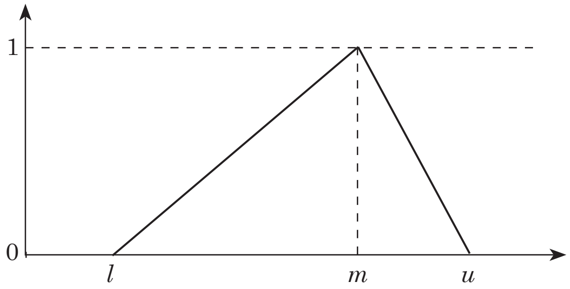

Figure 1. Triangular fuzzy number

Determining the linguistic variables

A linguistic variable is a variable whose values are words or sentences in a natural or artificial language (Sun, 2010). We use this type of expression to obtain the weight of criteria through two-by-two comparisons by nine-point linguistic scale, as presented in Table 1. In this study, triangular fuzzy number is employed to represent subjective pairwise comparisons of evaluation process in order to model the uncertainty.

Fuzzy AHP

AHP was first introduced by Saaty (1980) and is able to solve the decision making problems. AHP can decompose any complex problem into several sub-problems in terms of hierarchical levels where each level represents a set of criteria or attributes relative to each sub-problem. AHP utilize three principles to solve problems (Aydogan, 2011): (i) structure of the hierarchy, (ii) the matrix of pairwise comparison ratios, and (iii) the method for calculating weights. Based on its unique merit, this method is used in solving many sophisticated decision-making issues by different researchers (Bertolini et al., 2006; Ying et al., 2007; Kauko, 2007; Dong

Table 1. Membership function of linguistic variable

Intensity of importance	Fuzzy number	Linguistic variable	Membership function	Reciprocal scale
9	$\tilde{9}$	Perfect	(8,9,10)	(1/10,1/9,1/8)
8	$\tilde{8}$	Absolute	(7,8,9)	(1/9,1/8,1/7)
7	$\tilde{7}$	Very good	(6,7,8)	(1/8,1/7,1/6)
6	$\tilde{6}$	Fairly good	(5,6,7)	(1/7,1/6,1/5)
5	$\tilde{5}$	Good	(4,5,6)	(1/6,1/5,1/4)
4	$\tilde{4}$	Preferable	(3,4,5)	(1/5,1/4,1/3)
3	$\tilde{3}$	Not bad	(2,3,4)	(1/4,1/3,1/2)
2	$\tilde{2}$	Weak advantage	(1,2,3)	(1/3,1/2,1)
1	$\tilde{1}$	Equal	(1,1,1)	(1,1,1)

et al., 2008; Lin et al., 2008; Wong and Li, 2008; Arunraj and Maiti, 2010; Dong et al., 2010; Plebankiewicz, 2009; Lin, 2010; Podvezko et al., 2010; Ulubeyli and Kazaz, 2009; Sivilevičius and Maskeliūnaitė, 2010; Medineckienė et al., 2010; Fouladgar et al, 2011).

However, the pure AHP model has been considerably criticized for a variety of reasons (Sun, 2010; Toosi and Kohanali, 2011). Significant criticisms include but are not limited to the following:

AHP is not capable to handle the uncertainty associated with the mapping of human judgment to a number by natural language, the subjective judgment by perception, evaluation, improvement and selection based on preference of decision-makers have great influence on the AHP results, and the ranking of the AHP method is rather imprecise. To overcome these problems, researchers combined the AHP technique with fuzzy theory to take into account the uncertainty (Aghataher et al., 2008; Wang et al., 2008; Cebeci, 2009; Li and Huang, 2009; Torfi et al., 2010; Wang et al., 2010; Isaai et al., 2011; Lee et al., 2011; Kilincci and Onal, 2011; Rostamzadeh and Sofian, 2011; Yang et al., 2011; Jung, 2011; Manekar et al., 2011; Chen et al., 2011; An et al., 2011).

Yang et al. (2011) proposed a hybrid approach using fuzzy inference system and fuzzy AHP which serves as a robust tool for the prioritization of different issues. The procedure for determining the importance of dimension by FAHP can be defined as follows (Sun, 2010; Chen et al., 2011):

Step 1: Form pairwise comparison matrices among all the criteria. Determine linguistic terms to the pairwise comparisons by asking which is the more important of each two dimensions based on Table 1, as following matrix $\tilde{A}$:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{n1} & 1/\tilde{a}_{n2} & \cdots & 1 \end{bmatrix}, \tag{2}$$

where

$$\tilde{a}_{ij} = \begin{cases} \tilde{9}^{-1}, \tilde{8}^{-1}, \tilde{7}^{-1}, \tilde{6}^{-1}, \tilde{5}^{-1}, \tilde{4}^{-1}, \tilde{3}^{-1}, \tilde{2}^{-1}, \tilde{1}, \tilde{2}, \tilde{3}, \tilde{4}, \tilde{5}, \tilde{6}, \tilde{7}, \tilde{8}, \tilde{9}, & i \neq j, \\ 1 & i = j. \end{cases} \tag{3}$$

Step 2: Calculate the fuzzy weights of each criterion by geometric mean technique (Buckley, 1985; Hsieh et al., 2004; Wu et al., 2009) that is:

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \cdots \tilde{a}_{ij} \otimes \cdots \otimes \tilde{a}_{in})^{1/n}, \quad (4)$$

$$\tilde{w}_i = \tilde{r}_1 \otimes [\tilde{r}_1 \oplus \cdots \oplus \tilde{r}_i \oplus \cdots \oplus \tilde{r}_n]^{-1}, \quad (5)$$

where: $\tilde{a}_{ij}$ is fuzzy comparison value of dimension i to criterion j, thus, $\tilde{r}_i$ is a geometric mean of fuzzy comparison value of criterion i to each criterion; $\tilde{w}_i$ is the fuzzy weight of the i^{th} criterion, can be indicated by a triangular fuzzy number; $\tilde{w}_i = (lw_i, mw_i, uw_i)$. Here: lw_i, mw_i and uw_i are the lower, middle, and upper values of the fuzzy weight of the i^{th} dimension, respectively.

The output of fuzzy synthetic decisions obtained by each dimension is a fuzzy number. Therefore, it is necessary to convert fuzzy numbers into crisp numbers by defuzzification in order to compare the rank of dimensions. The procedure of defuzzification is to locate the Best Nonfuzzy Performance (BNP) value. Methods of such defuzzified fuzzy ranking generally include mean of maximal (MOM), center of area (COA), and α-cut (Chen et al., 2011).

In this study, the authors employ the center of area (COA) method to prioritize the order of importance of each dimension. This method is a simple and practical without the need to bring in the preferences of any evaluators (Wu et al., 2009). The BNP value for the fuzzy number $\tilde{R}_i = (L\tilde{R}_i, M\tilde{R}_i, U\tilde{R}_i)$ can be found using the following equation:

$$BNP_i = [(U\tilde{R}_i - L\tilde{R}_i) + (M\tilde{R}_i - L\tilde{R}_i)]/3 + L\tilde{R}_i. \quad (6)$$

4. COPRAS (COmplex PRoportional ASsessment) METHOD (Zavadskas and Kaklauskas, 1996)

The COPRAS method determines a solution with the ratio to the best solution.

The algorithm of the COPRAS method is shown in the Figure 2.

1. Selection of the available set most important attributes, which describes alternatives;

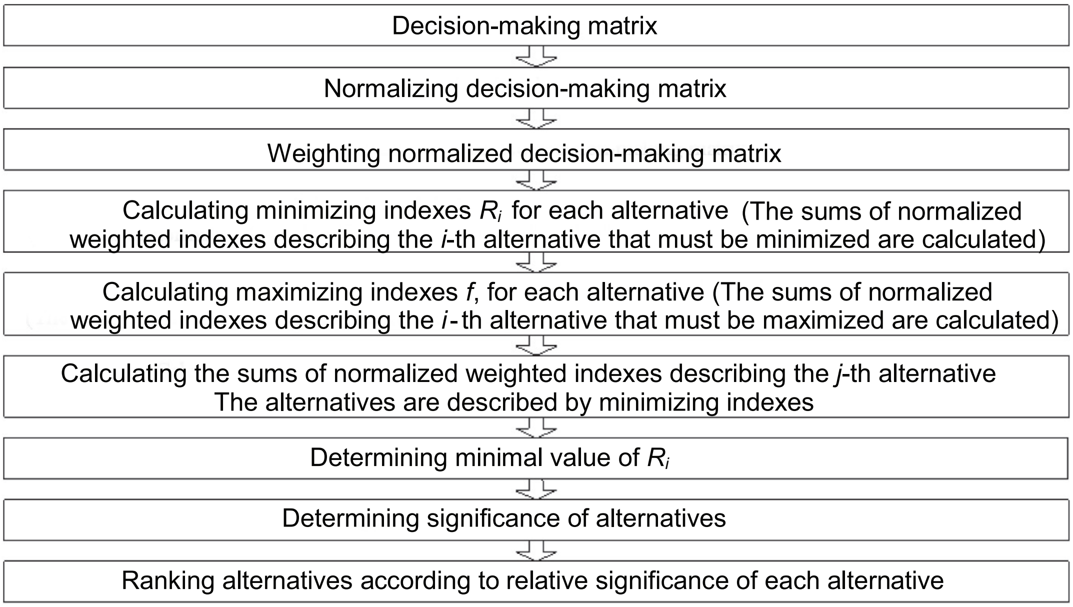

Figure 2. Ranking of alternatives by applying COPRAS method

2. Preparing of the decision-making matrix *X*:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix}; \; i = \overline{1,n} \; and \; j = \overline{1,m}, \quad (7)$$

where: attribute j is in the alternative i of a solution; m is the number of attributes; n is the number of the alternatives compared.

3. Determining weights of the attributes q_j.
4. Normalization of the decision-making matrix $\overline{X}$. The normalized values of this matrix (Zavadskas, 1987) are calculated as:

$$\overline{x}_{ij} = \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}}; \; i = \overline{1,n} \; and \; j = \overline{1,m}. \quad (8)$$

After this step we have normalized decision-making matrix:

$$\overline{X} = \begin{bmatrix} \overline{x}_{11} & \overline{x}_{12} & \cdots & \overline{x}_{1m} \\ \overline{x}_{12} & \overline{x}_{22} & \cdots & \overline{x}_{2m} \\ \vdots & \vdots & \cdots & \vdots \\ \overline{x}_{n1} & \overline{x}_{n2} & \cdots & \overline{x}_{nm} \end{bmatrix}. \quad (9)$$

5. Calculation of the weighted normalized decision matrix $\hat{X}$. The weighted normalized values $\hat{x}_{ij}$ are calculated as:

$$\hat{x}_{ij} = \overline{x}_{ij} \cdot q_j; \; i = \overline{1,n} \; and \; j = \overline{1,m}. \quad (10)$$

In formula (10) q_j is weight of the $j - th$ attribute.

After this step we have weighted normalized decision-making matrix:

$$\hat{X} = \begin{bmatrix} \hat{x}_{11} & \hat{x}_{12} & \cdots & \hat{x}_{1m} \\ \hat{x}_{21} & \hat{x}_{22} & \cdots & \hat{x}_{2m} \\ \vdots & \vdots & \cdots & \vdots \\ \hat{x}_{n1} & \hat{x}_{n2} & \cdots & \hat{x}_{nm} \end{bmatrix}; \; i = \overline{1,n} \; and \; j = \overline{1,m}. \quad (11)$$

6. Sums P_j of attributes values which larger values are more preferable (optimization direction is maximization) calculation for each alternative (line of the decision-making matrix):

$$P_i = \sum_{j=1}^{k} \hat{x}_{ij}. \quad (12)$$

In formula (12) K is number of attributes which must to be maximised (it is assumed that in the decision-making matrix columns first of all are placed attributes with optimization direction maximum and ones with optimization direction minimum are placed after).

7. Sums R_i of attributes values which smaller values are more preferable (optimization direction is minimization) calculation for each alternative (line of the decision-making matrix):

$$R_i = \sum_{j=k+1}^{m} \hat{x}_j. \quad (13)$$

In formula (13) $(m-k)$ is number of attributes which must to be minimized.

8. Determining the minimal value of R_i:

$$R_{\min} = \min_i R_i; \; i = \overline{1,n}. \quad (14)$$

9. Calculation of the relative weight of each alternative Q_i:

$$Q_i = P_i + \frac{R_{\min} \sum_{i=1}^{n} R_i}{R_i \sum_{i=1}^{n} \frac{R_{\min}}{R_i}}. \quad (15^*)$$

Formula (15) can to be written as follows:

$$Q_i = P_i + \frac{\sum_{i=1}^{n} R_i}{R_i \sum_{i=1}^{n} \cdot \frac{1}{R_i}}. \quad (15)$$

10. Determination of the optimality criterion *K*:

$$K = \max_i Q_i;\ i = \overline{1,n}. \quad (16)$$

11. Determination of the priority of the project. The greater weight (relative weight of alternative) Q_i, the higher is the priority (rank) of the project. In the case of $Q_{\max}$, the satisfaction degree is the highest.
12. Calculation of the utility degree of each alternative:

$$N_i = \frac{Q_i}{Q_{\max}} 100\%, \quad (17)$$

where: Q_i and $Q_{\max}$ are the weight of projects obtained from formula (15).

5. THE PROPOSED MODEL

In this paper, fuzzy AHP and COPRAS are employed as an integrated methodology for selecting the optimal maintenance strategy. The proposed model includes three steps: (1) determining the weights of evaluation criteria by fuzzy AHP, (2) evaluating the preference rating of alternatives, and (3) ranking the alternatives and choosing the optimal maintenance strategy. In the first step, fuzzy AHP is carried out by decomposing the structure of decision process into a hierarchical structure in order to determine the importance of each criterion through pairwise comparisons and based on linguistic terms. After constructing hierarchical structure and calculating the weights of criteria, the importance of alternatives are evaluated via the COPRAS technique. Finally, according to the results of COPRAS method, alternatives are ranked in descending order and the best alternative is selected. Schematic diagram of the proposed model for selecting the optimal maintenance strategy is shown in Figure 3.

6. CASE STUDY

Sungun copper mine is one of the largest copper deposits of Iran which is located in east Azerbijan province in mountainous area and North West of Ahar city. The location of Sungun copper mine in Iran is depicted in Figure 4. Mine is connected to Tabriz city through a road that is about 125 km (Bazzazi et al., 2009). This deposit is in the middle of Qarabagh Mountains that highest altitude of the area from open sea is about 2390 m. Feasibility studies were shown that open-pit mining is the most suitable method for this deposit and an amount of about 384 million tons of ore at an average grade of 0.665 % copper with the waste to ore ratio of 1.8:1.0. The mine's life span is estimated at 31 years, with an annual production of 7 million tons in the first 5 years and about 14 million tons for remaining years of mine's life (Hoseinie et al., 2006).

Through technical and economical studies, shovel and truck have been selected as the optimum loading and hauling equipment in this mine. 30 and 100 tons Komatsu dump trucks are used for material handling operation[1].

7. THE IMPLEMENTATION OF PROPOSED MODEL

Regarding the evaluation of dump truck maintenance strategies in Sungun copper mine, 8 experts were invited to evaluate five alternatives using the proposed model shown in Figure 3. According to the literature investigation and expert's opinions, the committee finally adopted 12 criteria. This study contains 12 evaluation criteria including Spare part stocks (C1), Personnel wage (C2), Mean time to repair (C3), Mean time between failures (C4), Product loss (R1), People damage (R2), Environmental damage (R3), Technology (AC1), Human resource (AC2), Product quality (AV1), Efficiency (AV2), and Intrinsic safety (AV3). The first seven criteria are cost criteria, while the last five are benefit ones.

[1] www.mbinco.com

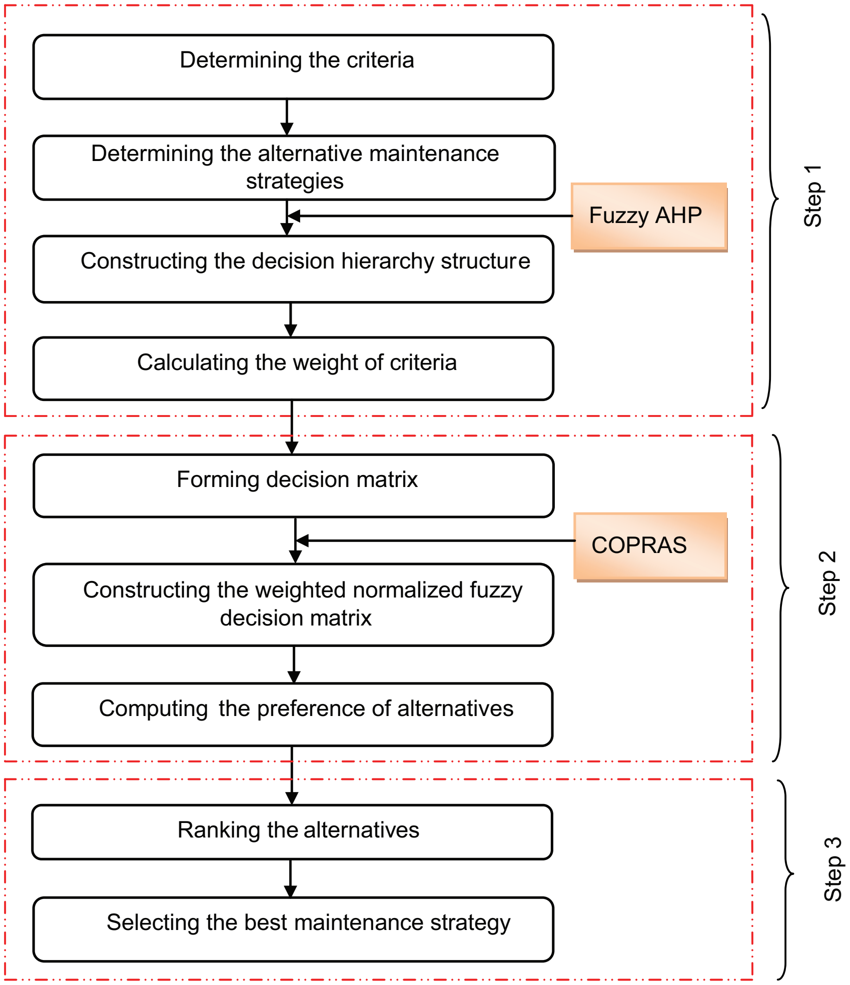

Figure 3. The proposed model

Figure 4. Location map of Sungun copper mine in Iran (Bidhendi et al., 2007)

After constructing the structure of hierarchy as depicted in Figure 5, the weights of evaluation criteria are calculated using the fuzzy AHP approach. The comparison of the importance or preference of one criterion or alternative over another can be accomplished with the help of questionnaire. The priority weights of the feasible alternatives are obtained based on following computations.

Calculating the weight of each criterion

We adopt fuzzy AHP method to evaluate the weights of evaluation criteria for the maintenance strategies for dump trucks. The decision makers group contains of 8 experts with minimum 7 years experience in the field of maintenance were invited to fill the judgment matrix.

The fuzzy pairwise comparison matrix of the main and sub-criteria are obtained based on Table 1 by asking which is more important. Then, the elements of synthetic pairwise comparison matrix are calculated by using the geometric technique introduced by Buckley (1985). This technique computes the geometric mean of the fuzzy comparison values of one criterion over another. The computation of the elements of synthetic pairwise comparison matrix by using the geometric mean method is obtained as follows matrices.

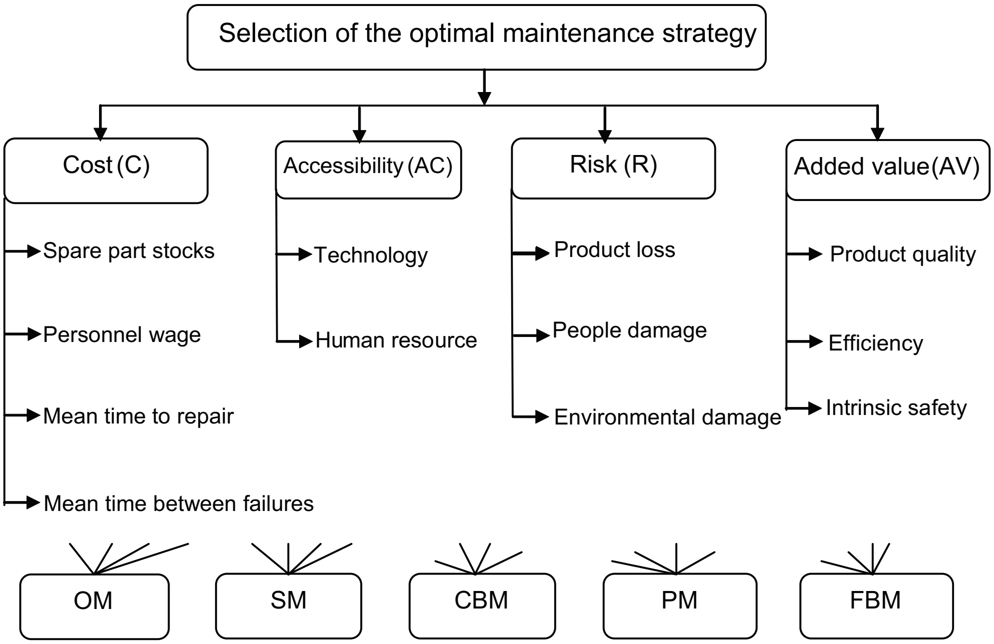

Figure 5. Structure of hierarchy

$$A = \begin{array}{r} \\ Cost \\ Risk \\ Accessability \\ Added\ value \end{array} \begin{array}{c} \begin{array}{cccc} \scriptstyle Cost & \scriptstyle Risk & \scriptstyle Accessability & \scriptstyle Added\ value \end{array} \\ \begin{bmatrix} (1,1,1) & (0.95,1.25,1.56) & (2.27,3.38,4.44) & (1.19,2.21,3.22) \\ (0.64,0.79,1.05) & (1,1,1) & (2.1,3.19,4.23) & (1.19,1.86,2.44) \\ (0.22,0.29,0.44) & (0.23,0.31,0.47) & (1,1,1) & (0.53,0.64,0.84) \\ (0.31,0.45,0.84) & (0.41,0.54,0.84) & (1.19,1.56,1.86) & (1,1,1) \end{bmatrix} \end{array}$$

$$A_{Cost} = \begin{array}{c} \\ C1 \\ C2 \\ C3 \\ C4 \end{array} \begin{array}{c} \begin{array}{cccc} C1 & C2 & C3 & C4 \end{array} \\ \begin{bmatrix} (1,1,1) & (0.82,1.25,1.79) & (0.52,0.67,0.92) & (0.54,0.64,0.87) \\ (0.55,0.79,1.2) & (1,1,1) & (0.53,0.69,0.96) & (0.52,0.62,0.79) \\ (1.09,1.48,1.91) & (1.03,1.43,1.86) & (1,1,1) & (0.69,0.91,1.25) \\ (1.14,1.54,1.84) & (1.25,1.62,1.91) & (0.79,1.09,1.43) & (1,1,1) \end{bmatrix} \end{array}$$

$$A_{Risk} = \begin{array}{c} \\ R1 \\ R2 \\ R3 \end{array} \begin{array}{c} \begin{array}{ccc} R1 & R2 & R3 \end{array} \\ \begin{bmatrix} (1,1,1) & (0.63,0.79,1.05) & (0.87,1.29,1.73) \\ (0.95,1.25,1.56) & (1,1,1) & (1.13,1.64,2.21) \\ (0.57,0.77,1.15) & (0.45,0.61,0.88) & (1,1,1) \end{bmatrix} \end{array}$$

$$A_{Accessability} = \begin{array}{c} \\ AC1 \\ AC2 \end{array} \begin{array}{c} \begin{array}{cc} AC1 & AC2 \end{array} \\ \begin{bmatrix} (1,1,1) & (0.75,0.92,1.15) \\ (0.87,1.09,1.31) & (1,1,1) \end{bmatrix} \end{array}$$

$$A_{Added\ value} = \begin{array}{c} \\ AV1 \\ AV2 \\ AV3 \end{array} \begin{array}{c} \begin{array}{ccc} AV1 & AV2 & AV3 \end{array} \\ \begin{bmatrix} (1,1,1) & (0.66,0.92,1.31) & (0.87,1.19,1.51) \\ (0.95,1.25,1.56) & (1,1,1) & (0.87,1.29,1.73) \\ (0.66,0.84,1.15) & (0.57,0.77,1.14) & (1,1,1) \end{bmatrix} \end{array}$$

The fuzzy weights of the dimensions are calculated as following part.

$\tilde{r}_{Cost} = (1.266,1.749,2.175)$; $\tilde{r}_{Risk} = (1.124,1.476,1.817)$; $\tilde{r}_{Accessability} = (0.411,0.493,0.647)$;

$\tilde{r}_{Added\ value} = (0.623,0.785,1.071)$;

$\tilde{r}_{C1} = (0.695,0.859,1.094)$; $\tilde{r}_{C2} = (0.628,0.765,0.982)$; $\tilde{r}_{C3} = (0.942,1.182,1.453)$;

$\tilde{r}_{C4} = (1.034,1.285,1.5)$;

$\tilde{r}_{R1} = (0.822,1.012,1.221)$; $\tilde{r}_{R2} = (1.024,1.272,1.513)$; $\tilde{r}_{R3} = (0.638,0.776,1.004)$;

$\tilde{r}_{AC1} = (0.871,0.957,1.071)$; $\tilde{r}_{AC2} = (0.933,1.044,1.147)$;

$\tilde{r}_{AV1} = (0.832,1.029,1.257)$; $\tilde{r}_{AV2} = (0.871,1.122,1.377)$; $\tilde{r}_{AV3} = (0.725,0.865,1.095)$.

The relative importance of each criterion is calculated by using formula (5) and the results are listed in Table 2. The fuzzy weights for each criterion are transferred into the BNP value by the COA method as presented in Table 2. It can be inferred from the fuzzy AHP results that the first two important criteria for the evaluation of maintenance strategies are people damage (0.171) and mean time between failures (0.152). Moreover, the less important criterion is technology (0.064). The final ranking of criteria is schematically depicted in Figure 6.

Evaluate the alternatives with COPRAS

During the decision procedure, the decision maker team was asked to fill the decision matrix by comparing alternatives with respect to each of the criteria one by one. The decision matrix based on expert knowledge is formed in order to evaluate the possible alternatives. The decision makers use the linguistic rating variables shown in Table 3 to evaluate the rating of alternatives with respect to each criterion. A sample of the decision matrix filled by one of the experts is shown in Table 4.

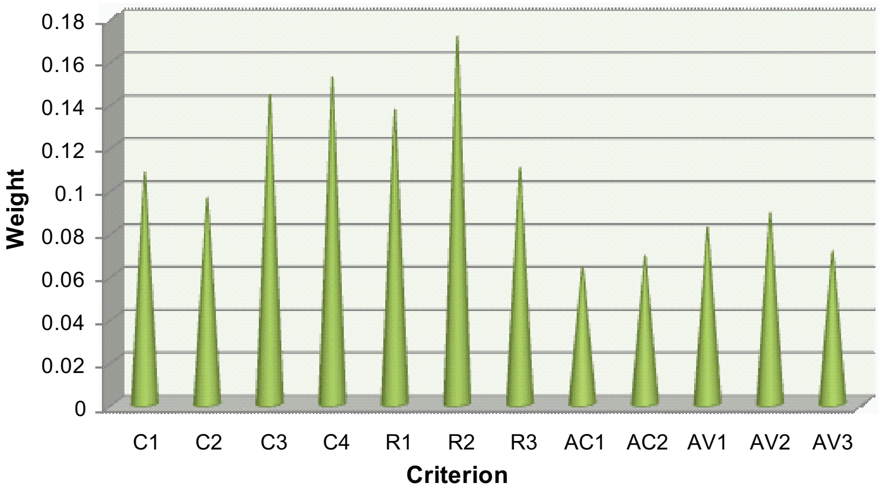

Figure 6. The final ranking of the criteria

Table 2. Fuzzy weights of evaluation criteria by FAHP

Criteria		Local weights	Global weights	BNP	Rank
Cost		(0.221,0.388,0.635)		0.415	1
C1	x_1	(0.138,0.209,0.331)	(0.03,0.081,0.21)	0.108	6
C2	x_2	(0.125,0.187,0.297)	(0.027,0.072,0.188)	0.096	7
C3	x_3	(0.187,0.289,0.44)	(0.041,0.112,0.279)	0.144	3
C4	x_4	(0.205,0.314,0.454)	(0.045,0.121,0.288)	0.152	2
Risk		(0.196,0.327,0.53)		0.351	2
R1	x_5	(0.22,0.33,0.491)	(0.043,0.108,0.26)	0.137	4
R2	x_6	(0.273,0.415,0.608)	(0.053,0.136,0.323)	0.171	1
R3	x_7	(0.17,0.253,0.404)	(0.033,0.083,0.214)	0.11	5
Accessibility		(0.072,0.109,0.189)		0.123	4
AC1	x_8	(0.392,0.478,0.593)	(0.028,0.052,0.112)	0.064	12
AC2	x_9	(0.42,0.521,0.635)	(0.03,0.057,0.12)	0.069	11
Added value		(0.109,0.174,0.312)		0.198	3
AV1	x_{10}	(0.223,0.341,0.517)	(0.024,0.059,0.161)	0.082	9
AV2	x_{11}	(0.223,0.372,0.566)	(0.025,0.064,0.177)	0.089	8
AV3	x_{12}	(0.194,0.286,0.45)	(0.021,0.049,0.141)	0.071	10
			$\sum$	1.293	

Table 3. Definition and membership function of fuzzy numbers

Linguistic variable	Triangular fuzzy number
Very low (VL)	(0,1,3)
Low (L)	(1,3,5)
Medium (M)	(3,5,7)
High (H)	(5,7,9)
Very high (VH)	(7,9,10)

The linguistic values of expert's opinion are converted into triangular fuzzy numbers. To construct the decision matrix and determine the rank of maintenance strategies, the aggregated fuzzy rating of alternatives is calculated through formula (7):

$$\tilde{x}_{ij} = (x_{ij1}, x_{ij2}, x_{ij3})$$

where:

$$x_{ij1} = \min_k \{x_{ijk1}\},\ x_{ij2} = \frac{1}{K}\sum_{k=1}^{K} x_{jk2},\ x_{ij3} = \max_k \{x_{ijk3}\}$$

And the fuzzy rating of the k th decision maker is $\tilde{x}_{ijk} = (x_{ijk1}, x_{ijk2}, x_{ijk3})$.

The ratings of the five maintenance strategies by the decision makers under the different criteria are presented in Table 5. Then, Crisp values for decision matrix are obtained by formula (6) as shown in Table 6.

Table 4. A sample of decision matrix filled

	Effect	FBM	PM	CBM	SM	OM
x_1	–	VL	VH	H	M	L
x_2	–	H	M	L	VL	L
x_3	–	VH	M	M	L	H
x_4	–	VH	VL	M	L	M
x_5	–	VH	VL	L	M	L
x_6	–	H	L	M	VL	M
x_7	–	M	H	M	L	L
x_8	+	VH	VL	M	H	H
x_9	+	H	L	M	M	M
x_{10}	+	L	VH	H	H	M
x_{11}	+	M	H	VH	VH	H
x_{12}	+	VL	VH	H	H	M

Table 5. Aggregated fuzzy rating of maintenance strategies

	FBM	PM	CBM	SM	OM
x_1	(0,2.32,7)	(5,7.21,10)	(3,5.67,10)	(1,4.12,7)	(0,3.44,7)
x_2	(5,6.86,10)	(1,4.97,9)	(0,3.56,7)	(0,2.43,5)	(0,4.13,7)
x_3	(5,7.23,10)	(1,5.64,9)	(1,3.95,7)	(0,3.32,7)	(5,6.48,10)
x_4	(3,6.73,10)	(0,2.13,5)	(1,5.34,9)	(0,4.21,9)	(0,3.46,7)
x_5	(5,7.72,10)	(0,1.27,5)	(0,3.58,7)	(1,4.39,9)	(0,3.77,9)
x_6	(3,6.24,10)	(0,3.12,7)	(1,4.87,9)	(0,1.89,5)	(0,3.62,7)
x_7	(1,5.16,9)	(3,6.75,10)	(0,4.33,9)	(0,2.57,7)	(0,3.23,7)
x_8	(3,7.34,10)	(0,2.16,7)	(1,4.76,9)	(3,6.82,10)	(3,7.11,10)
x_9	(1,6.57,10)	(0,3.25,7)	(1,4.87,9)	(1,4.37,7)	(1,6.13,9)
x_{10}	(0,3.28,7)	(3,6.76,10)	(3,5.96,10)	(1,5.24,9)	(1,4.26,9)
x_{11}	(1,4.36,9)	(3,6.79,10)	(5,7.34,10)	(3,6.17,10)	(3,6.12,10)
x_{12}	(0,2.31,5)	(3,7.38,10)	(1,5.96,10)	(3,6.42,10)	(1,5.26,9)

Table 6. Crisp values for decision matrix

Criteria	Alternative maintenance strategies				
	FBM	PM	CBM	SM	OM
	S_1	2	3	4	5
x_1	3.11	7.4	6.22	4.04	3.48
x_2	7.28	4.99	3.52	2.47	3.71
x_3	7.74	5.21	3.98	3.44	7.16
x_4	6.57	2.37	5.11	4.4	3.48
x_5	7.57	2.09	3.53	4.79	4.25
x_6	6.41	3.37	4.95	2.29	3.54
x_7	5.05	6.58	4.44	3.19	3.41
x_8	6.78	3.05	4.92	6.6	6.7
x_9	5.85	3.41	4.95	4.12	5.37
x_{10}	3.42	6.58	6.32	5.08	4.75
x_{11}	4.78	6.59	7.44	6.39	6.37
x_{12}	2.43	6.79	5.65	6.47	5.08

Table 7. The problem's solution according to COPRAS method

Initial decision-making matrix with values of the attributes describing the compared alternatives															
Strat.	Criteria														
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}			
Opt.	*min*	*min*	*min*	*min*	*min*	*min*	*min*	*max*	*max*	*max*	*max*	*max*			
Weight q_j	0.108	0.096	0.144	0.152	0.137	0.171	0.11	0.064	0.069	0.082	0.089	0.071			
1	3.11	7.28	7.74	6.57	7.57	6.41	5.05	6.78	5.85	3.42	4.78	2.43			
2	7.4	4.99	5.21	2.37	2.09	3.37	6.58	3.05	3.41	6.58	6.59	6.79			
3	6.22	3.52	3.98	5.11	3.53	4.95	4.44	4.92	4.95	6.32	7.44	5.65			
4	4.04	2.47	3.44	4.4	4.79	2.29	3.19	6.6	4.12	5.08	6.39	6.47			
5	3.48	3.71	7.16	3.48	4.25	3.54	3.41	6.7	5.37	4.75	6.37	5.08			
$\sum$	24.25	21.97	27.53	21.93	22.23	20.56	22.67	28.05	23.7	26.15	31.57	26.42			
Weighted normalized matrix													Q	N	Rank
1	0.014	0.032	0.040	0.046	0.047	0.053	0.025	0.015	0.017	0.011	0.013	0.007	0.175	60.8	5
2	0.033	0.022	0.027	0.016	0.013	0.028	0.032	0.007	0.010	0.021	0.019	0.018	0.222	77.2	4
3	0.028	0.015	0.021	0.035	0.022	0.041	0.022	0.011	0.014	0.020	0.021	0.015	0.226	78.6	3
4	0.018	0.011	0.018	0.030	0.030	0.019	0.015	0.015	0.012	0.016	0.018	0.017	0.288	100.0	1
5	0.015	0.016	0.037	0.024	0.026	0.029	0.017	0.015	0.016	0.015	0.018	0.014	0.245	85.3	2

After 12-th solution step final solution results as are as shown in Table 7 and Figure 7.

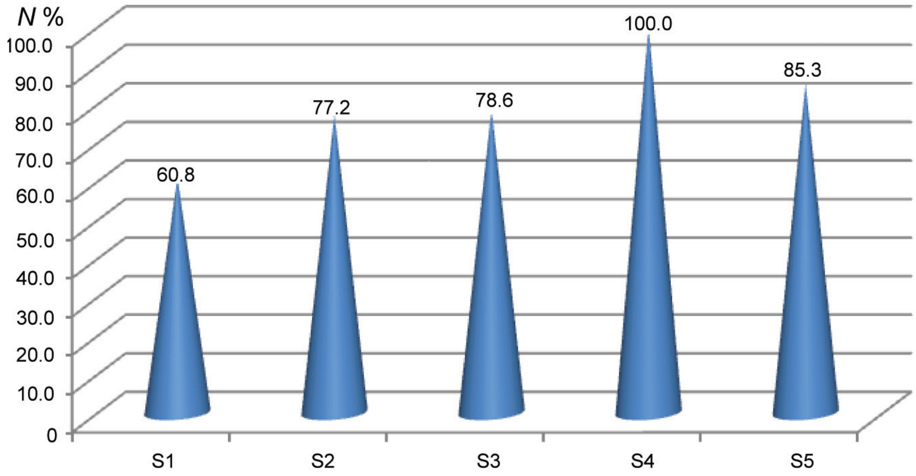

Figure 7. Graphic representation of alternatives' ranking according to COPRAS methods

According to solution results we can to state, is we will perform calculations with optimistic, pessimistic and grey values the results will be different (Figure 7). The alternatives ranks as follows: $A_4 \succ A_5 \succ A_3 \succ A_2 \succ A_1$. The best 4th alternative is selected according to the COPRAS method.

8. CONCLUSION

Maintenance strategy selection is a critical management problem because of its significant roles in production and manufacturing. Therefore, the accuracy in selecting the most appropriate maintenance strategy is one of the maintenance goals. The maintenance strategy selection problem is often influenced by uncertainty in real world, and in such circumstances fuzzy set theory is a proper tool to face with this type of problems and model the existing uncertainty. In practice, it is difficult or even impossible for decision makers to express the precise numerical information on the weights and the ratings; for this reason, the linguistic terms are useful.

This study has proposed a new fuzzy MCDM method based on combining the concepts of COPRAS and AHP, which fuzzy AHP is applied to assign the weights of evaluation criteria and COPRAS technique is used to rank the feasible maintenance strategies. A real case study of maintenance strategy selection in Sungun copper mine has been illustrated to demonstrate the applicability of the proposed method. It appears this method has some advantages which may be useful in facing with maintenance strategy selection problem.

Although the proposed method described in detail is shown by a problem of maintenance strategy selection in Sungun copper mine is very flexible, it can also be applied to other issues such as equipment selection, mining method selection, project selection, and many other different problems in connected with selection.

REFERENCES

Aghataher, R., Delavar, M. R., Nami, M. H. and Samnay, N. (2008) A Fuzzy-AHP decision support system for evaluation of cities vulnerability against earthquakes, *World Applied Sciences Journal*, 3(1), pp. 66–72.

Ahmadi, A., Söderholm, P. and Kumar, U. (2010) On aircraft scheduled maintenance program development, *Journal of Quality in Maintenance Engineering*, 16(3), pp. 229–255. doi:10.1108/13552511011072899

Almeida, A. T. and Bohoris, G. A. (1995) Decision theory in maintenance decision making, *Quality in Maintenance Engineering*, 1(1), pp. 39–45. doi:10.1108/13552519510083138

Al-Najjar, B. and Alsyouf, I. (2003) Selecting the most efficient maintenance approach using fuzzy multiple criteria decision making, *International Journal of Production Economics*, 84(1), pp. 85–100. doi:10.1016/S0925-5273(02)00380-8

An, M., Chen, Y. and Baker, C. J. (2011) A fuzzy reasoning and fuzzy-analytical hierarchy process based approach to the process of railway risk information: a railway risk management system, *Information Sciences*, Article in Press. doi:10.1016/j.ins.2011.04.051

Andrawus, J. A. (2008) *Maintenance optimization for wind turbines*. Ph.D thesis, The Robert Gordon University.

Arunraj, N. S. and Maiti, J. (2010) Risk-based maintenance policy selection using AHP and goal programming, *Safety Science*, 48(2), pp. 238–247. doi:10.1016/j.ssci.2009.09.005

Aydogan, E. K. (2011) Performance measurement model for Turkish aviation firms using the rough-AHP and TOPSIS methods under fuzzy environment, *Expert Systems with Applications*, 38(4), pp. 3992–3998. doi:10.1016/j.eswa.2010.09.060

Azadivar, F. and Shu, V. (1999) Maintenance policy selection for JIT production systems, *International Journal of Production Research*, 37(16), pp. 3725–3738. doi:10.1080/002075499190013

Bashiri, M., Badri, H. and Hejazi, T. H. (2011) Selecting optimum maintenance strategy by fuzzy interactive linear assignment method, *Applied Mathematical Modelling*, 35(1), pp. 152–164. doi:10.1016/j.apm.2010.05.014

Bazzazi, A. A., Osanloo, M. and Karimi, B. (2009) Optimal open pit mining equipment selection using fuzzy multiple attribute decision making approach, *Archive of Mining Science*, 54(2), pp. 301–320.

Bertolini, M. and Bevilacqua, M. (2006) A combined goal programming – AHP approach to maintenance selection problem, *Reliability Engineering & System Safety*, 91(7), pp. 839–848. doi:10.1016/j.ress.2005.08.006

Bertolini, M., Braglia, M. and Carmignani, G. (2006) Application of the AHP methodology in making a proposal for a public work contract, *International Journal of Project Management*, 24(5), pp. 422–430. doi:10.1016/j.ijproman.2006.01.005

Bevilacqua, M. and Braglia, M. (2000) The analytic hierarchy process applied to maintenance strategy selection, *Reliability Engineering and System Safety*, 70(1), pp. 71–83. doi:10.1016/S0951-8320(00)00047-8

Bidhendi, G. R. N., Karbassi, A. R., Nasrabadi, T. and Hoveidi, H. (2007) Influence of copper mine on surface water quality, *International Journal of Environmental Science and Technology*, 4(1), pp. 85–91.

Buckley, J. J. (1985) Fuzzy hierarchical analysis, *Fuzzy Sets and Systems*, 17(3), pp. 233–247. doi:10.1016/0165-0114(85)90090-9

Büyüközkan, G., Çifçi, G. and Güleryüz, S. (2011) Strategic analysis of healthcare service quality using fuzzy AHP methodology, *Expert Systems with Applications*, 38(8), pp. 9407–9424. doi:10.1016/j.eswa.2011.01.103

Cebeci, U. (2009) Fuzzy AHP-based decision support system for selecting ERP systems in textile industry by using balanced scorecard, *Expert Systems with Applications*, 36(5), pp. 8900–8909. doi:10.1016/j.eswa.2008.11.046

Chatterjee, P., Athawale, V. M. and Chakraborty, S. (2011) Materials selection using complex proportional assessment and evaluation of mixed data methods, *Materials and Design*, 32(2), pp. 851–860. doi:10.1016/j.matdes.2010.07.010

Chen, V. Y. C., Lien, H. P., Liu, C. H., Liou, J. J. H., Tzenge, G. H. and Yang, L. S. (2011) Fuzzy MCDM approach for selecting the best environment-watershed plan, *Applied Soft Computing*, 11(1), pp. 265–275. doi:10.1016/j.asoc.2009.11.017

Christer, A. H. and Lee, C. (2000) Refining the delay-time-based PM inspection model with non-negligible system downtime estimates of the expected number of failures, *International Journal of Production Economics*, 67(1), pp. 77–85. doi:10.1016/S0925-5273(00)00011-6

Dhillon, B. S. (2008) *Mining Equipment Reliability, Maintainability, and Safety*. Springer.

Dong, Y., Xu, Y., Li, H. and Dai, M. (2008) A comparative study of the numerical scales and the prioritization methods in AHP, *European*

Journal of Operational Research, 186(1), pp. 229–242. doi:10.1016/j.ejor.2007.01.044

Dong, Y., Zhang, G., Hong, W. C. and Xu, Y. (2010) Consensus models for AHP group decision making under row geometric mean prioritization method, *Decision Support Systems*, 49(3), pp. 281–289. doi:10.1016/j.dss.2010.03.003

Fouladgar, M. M., Yazdani-Chamzini, A. and Zavadskas, E. K. (2011) An integrated model for prioritizing strategies of the Iranian mining sector, *Technological and Economic Development of Economy*, 17(3), pp. 459–484. doi:10.3846/20294913.2011.603173

Gaonkar, R. S. P., Verma, A. K. and Srividya, A. (2008) Exploring fuzzy set concept in priority theory for maintenance strategy selection problem, *International Journal of Applied Management and Technology*, 6(3), pp. 131–142.

Hoseinie, S. S., Pourrahimian, Y. and Aghababae, H. (2006) Application of rock mass index (RMi) to determine of blasting index (BI) - a case study Sungun copper mine–Iran. In: *International conference on mine planning and equipment selection*, Torino, Italy, 19-22 September, pp. 1013–1018.

Hsieh, T.-Y., Lu, S.-T. and Tzeng, G.-H. (2004) Fuzzy MCDM approach for planning and design tenders selection in public office buildings, *International Journal of Project Management*, 22(7), pp. 573–584. doi:10.1016/j.ijproman.2004.01.002

Isaai, M. T., Kanani, A., Tootoonchi, M. and Afzali, H. R. (2011) Intelligent timetable evaluation using fuzzy AHP, *Expert Systems with Applications*, 38(4), pp. 3718–3723. doi:10.1016/j.eswa.2010.09.030

Jafari, A., Jafarian, M., Zareei, A. and Zaerpour, F. (2008) Using fuzzy delphi method in maintenance strategy selection problem, *Journal of Uncertain Systems*, 2(4), pp. 289–298.

Jung, H. (2011) A fuzzy AHP–GP approach for integrated production-planning considering manufacturing partners, *Expert Systems with Applications*, 38(5), pp. 5833–5840. doi:10.1016/j.eswa.2010.11.039

Kaklauskas, A., Zavadskas, E. K., Naimaviciene, J., Krutinis, M., Plakys, V. and Venskus, D. (2010) Model for a complex analysis of intelligent built environment, *Automation in Construction*, 19(3), pp. 326–340. doi:10.1016/j.autcon.2009.12.006

Kaklauskas, A., Zavadskas, E. K., Raslanas, S., Ginevicius, R., Komka, A. and Malinauskas, P. (2006) Selection of low-e windows in retrofit of public buildings by applying multiple criteria method COPRAS: A Lithuanian case, *Energy and Buildings*, 38(5), pp. 454–462. doi:10.1016/j.enbuild.2005.08.005

Kaklauskas, A., Rutė, J., Gudauskas, R. and Banaitis, A. (2011) Integrated model and system for passive houses multiple criteria analysis, *International Journal of Strategic Property Management*, 15(1), pp. 74–90. doi:10.3846/1648715X.2011.574903

Kauko, T. (2007) An analysis of housing location attributes in the inner city of Budapest, Hungary, using expert judgements, *International Journal of Strategic Property Management*, 11(4), pp. 209–225. doi:10.1080/1648715X.2007.9637570

Kilincci, O. and Onal, S. A. (2011) Fuzzy AHP approach for supplier selection in a washing machine company, *Expert Systems with Applications*, 38(8), pp. 9656–9664. doi:10.1016/j.eswa.2011.01.159

Khazraei, Kh. and Deuse, J. (2011) A strategic standpoint on maintenance taxonomy, *Journal of Facilities Management*, 9(2), pp. 96–113. doi:10.1108/14725961111128452

Laggoune, R., Chateauneuf, A. and Aissani, D. (2009) Opportunistic policy for optimal preventive maintenance of a multi-component system in continuous operating units, *Computers & Chemical Engineering*, 33(9), pp. 1499–1510. doi:10.1016/j.compchemeng.2009.03.003

Lee, S. K., Mogi, G., Lee, S. K. and Kim, J. W. (2011) Prioritizing the weights of hydrogen energy technologies in the sector of the hydrogen economy by using a fuzzy AHP approach, *International Journal of Hydrogen Energy*, 36(2), pp. 1897–1902. doi:10.1016/j.ijhydene.2010.01.035

Li, T. S. and Huang, H. H. (2009) Applying TRIZ and Fuzzy AHP to develop innovative design for automated manufacturing systems, *Expert Systems with Applications*, 36, pp. 8302–8312. doi:10.1016/j.eswa.2008.10.025

Lin, K.-L. (2010) Determining key ecological indicators for urban land consolidation, *International Journal of Strategic Property Management*, 14(2), pp. 89–103. doi:10.3846/ijspm.2010.08

Lin, M. C., Wang, C. C., Chen, M. S. and Chang, C. A. (2008) Using AHP and TOPSIS approaches in customer-driven product design process, *Computers in Industry*, 59(1), pp. 17–31. doi:10.1016/j.compind.2007.05.013

Madhuri, B. C., Chandulal, A. J. and Padmaja, M. (2010) Selection of best web site by applying COPRAS-G method, *International Journal of Computer Science and Information Technologies*, 1(2), pp. 138–146.

Manekar, P., Nandy, T., Sargaonkar, A., Rathi, B. and Karthik, M. (2011) FAHP ranking and selection of pretreatment module for membrane separation processes in textile cluster, *Bioresource Technology*, 102(2), pp. 558–566. doi:10.1016/j.biortech.2010.07.086

Mann, L., Saxena, A. and Knapp, G. M. (1995) Statistical-based or condition-based preventive maintenance?, *Journal of Quality in Maintenance Engineering*, 1(1), pp. 46–59. doi:10.1108/13552519510083156

Medineckienė, M., Turskis, Z. and Zavadskas, E. K. (2010) Sustainable construction taking into account the building impact on the environment, *Journal of Environmental Engineering and Landscape Management*, 18(2), pp. 118–127. doi:10.3846/jeelm.2010.14

Mobley, R. K. (2002) *An introduction to predictive maintenance*. Second ed., Elsevier Science, New York.

Moghaddam, K. S. and Usher, J. S. (2011) Preventive maintenance and replacement scheduling for repairable and maintainable systems using dynamic programming, *Computers & Industrial Engineering*, 60(4), pp. 654–665. doi:10.1016/j.cie.2010.12.021

Murthy, D. N. P. and Asgharizadeh, E. (1999) Optimal decision making in a maintenance service operation, *European Journal of Operational Research*, 116, pp. 259–273. doi:10.1016/S0377-2217(98)90202-8

Nichols, H. L. (1976) *Moving the Earth*. North Castle Books, Greenwich, CT.

Plebankiewicz, E. (2009) Contractor prequalification model using fuzzy sets, *Journal of Civil Engineering and Management*, 15(4), pp. 377–385. doi:10.3846/1392-3730.2009.15.377-385

Podvezko, V. (2011) The comparative analysis of MCDA methods SAW and COPRAS, *Inzinerine Ekonomika-Engineering Economics*, 22(2), pp. 134–146.

Podvezko, V., Mitkus, S. and Trinkūnienė, E. (2010) Complex evaluation of contracts for construction, *Journal of Civil Engineering and Management*, 16(2), pp. 287–297. doi:10.3846/jcem.2010.33

Rostamzadeh, R. and Sofian, S. (2011) Prioritizing effective 7Ms to improve production systems performance using fuzzy AHP and fuzzy TOPSIS (case study), *Expert Systems with Applications*, 38(5), pp. 5166–5177. doi:10.1016/j.eswa.2010.10.045

Savsar, M. (2011) Analysis and modeling of maintenance operations in the context of an oil filling plant, *Journal of Manufacturing Technology Management*, 22(5), pp. 679–697. doi:10.1108/17410381111134509

Saaty, T. L. (1980) *The analytic hierarchy process*. McGraw-Hill, New York.

Sayadi, A. R., Lashgari, A. and Basiri, M. H. (2010) Loading and hauling equipments maintenance cost estimation in surface mining. In: *1st International and workshop on eMaintenance*, Lulea, Sweden, pp. 212–217.

Sayadi, A.R., Lashgari, A. and Paraszczak, J. (2012) Hard-rock LHD cost estimation using single and multiple regressions based on principal component analysis, *Tunnelling and Underground Space Technology*, 27(1), pp. 133–141. doi:10.1016/j.tust.2011.08.006

Sivilevičius, H. and Maskeliūnaitė, L. (2010) The criteria for identifying the quality of passengers' transportation by railway and their ranking using AHP method, *Transport*, 25(4), pp. 368–381. doi:10.3846/transport.2010.46

Sun, C. C. (2010) A performance evaluation model by integrating fuzzy AHP and fuzzy TOPSIS methods, *Expert Systems with Applications*, 37(12), pp. 7745–7754. doi:10.1016/j.eswa.2010.04.066

Swanson, L. (2001) Linking maintenance strategies to performance, *International Journal of Production Economics*, 70(3), pp. 237–244. doi:10.1016/S0925-5273(00)00067-0

Tatari, O. and Skibniewski, M. J. (2006) Integrated agent based construction equipment management: conceptual design, *Journal of Civil Engineering and Management*, 12(3), pp. 231–236. doi:10.1080/13923730.2006.9636397

Toosi, N. M. and Kohanali, R. A. (2011) The study of airline service quality in the Qeshm free zone by fuzzy logic, *Journal of Mathematics and Computer Science*, 2(1), pp. 171–185.

Torfi, F., Farahani, R. Z. and Rezapour, S. (2010) Fuzzy AHP to determine the relative weights of evaluation criteria and Fuzzy TOPSIS to rank the alternatives, *Applied Soft Computing*, 10(2), pp. 520–528. doi:10.1016/j.asoc.2009.08.021

Torlak, G., Sevkli, M., Sanal, M. and Zaim, S. (2011) Analyzing business competition by using fuzzy TOPSIS method: an example of Turkish domestic airline industry, *Expert Systems with Applications*, 38(4), pp. 3396–3406. doi:10.1016/j.eswa.2010.08.125

Tupenaite, L., Zavadskas, E. K., Kaklauskas, A., Turskis, Z. and Seniut, M. (2010) Multiple criteria assessment of alternatives for built and human environment renovation, *Journal of Civil Engineering and Management*, 16(2), pp. 257–266. doi:10.3846/jcem.2010.30

Ulubeyli, S. and Kazaz, A. (2009) A multiple criteria decision - making approach to the selection of concrete pumps, *Journal of Civil Engineering and Management*, 15(4), pp. 369–376. doi:10.3846/1392-3730.2009.15.369-376

Uzsilaityte, L. and Martinaitis, V. (2010) Search for optimal solution of public building renovation in terms of life cycle, *Journal of Environment Engineering and Landscape Management*, 18(2), pp. 102–110. doi:10.3846/jeelm.2010.12

Wang, J., Fan, K. and Wang, W. (2010) Integration of fuzzy AHP and FPP with TOPSIS methodology for aeroengine health assessment, *Expert Systems with Applications*, 37(12), pp. 8516–8526. doi:10.1016/j.eswa.2010.05.024

Wang, L., Chu, J. and Wu, J. (2007) Selection of optimum maintenance strategies based on a fuzzy analytic hierarchy process, *International Journal of Production Economics*, 107(1), pp. 151–163. doi:10.1016/j.ijpe.2006.08.005

Wang, Y. M., Luo, Y. and Hua, Z. (2008) On the extent analysis method for fuzzy AHP and its applications, *European Journal of Operational Research*, 186(2), pp. 735–747. doi:10.1016/j.ejor.2007.01.050

Veldman, J., Klingenberg, W. and Wortmann, H. (2011) Managing condition-based maintenance technology: a multiple case study in the process industry, *Journal of Quality in Maintenance Engineering*, 17(1), pp. 40–62. doi:10.1108/13552511111116240

Wong, J. K. W. and Li, H. (2008) Application of the analytic hierarchy process (AHP) in multi-criteria analysis of the selection of intelligent building systems, *Building and Environment*, 43(1), pp. 108–125. doi:10.1016/j.buildenv.2006.11.019

Wu, H. Y., Tzeng, G. H. and Chen, Y. H. (2009) A fuzzy MCDM approach for evaluating banking performance based on balanced scorecard, *Expert Systems with Applications*, 36(6), pp. 10135–10147. doi:10.1016/j.eswa.2009.01.005

Yang, M., Khan, F. I. and Sadiq, R. (2011) Prioritization of environmental issues in offshore oil and gas operations: a hybrid approach using fuzzy inference system and fuzzy analytic hierarchy process, *Process Safety and Environmental Protection*, 89(1), pp. 22–34. doi:10.1016/j.psep.2010.08.006

Ying, X., Zeng, G. M., Chen, G. Q., Tang, L., Wang, K.-L. and Huang, D.-Y. (2007) Combining AHP with GIS in synthetic evaluation of eco-environment quality—a case study of Hunan Province, China, *Ecological Modelling*, 209(2-4), pp. 97–109. doi:10.1016/j.ecolmodel.2007.06.007

Zadeh, L. A. (1965) Fuzzy sets, *Information and Control*, 8(3), pp. 338–353. doi:10.1016/S0019-9958(65)90241-X

Zadeh, L. A. (1975a) Fuzzy logic and its application to approximate reasoning, Part I, *Information Science*, 8(3), pp. 199–249. doi:10.1016/0020-0255(75)90036-5

Zadeh, L. A. (1975b) Fuzzy logic and its application to approximate reasoning, Part II, *Information Science*, 8(4), pp. 301–357. doi:10.1016/0020-0255(75)90046-8

Zadeh, L. A. (1975c) Fuzzy logic and its application to approximate reasoning, Part III, *Information Science*, 9(1), pp. 43–80. doi:10.1016/0020-0255(75)90017-1

Zavadskas, E. K. (1987) *Complex estimation and choice of resource saving decisions in construction*. Vilnius: Mokslas. (In Russian)

Zavadskas, E. K. and Kaklauskas, A. (1996) Determination of an efficient contractor by using the new method of multicriteria assessment. In: Langford, D. A. and Retik, A. (eds.) *International symposium for "The organisation and management of construction". Shaping theory and practice. Vol. 2: Managing the construction project and managing risk*. CIB W 65; London: E and FN SPON, pp. 94–104.

Zavadskas, E. K., Kaklauskas, A., Turskis, Z. and Tamosaitiene, J. (2009a) Multi-Attribute Decision-Making model by applying grey numbers, *Informatica*, 20(2), pp. 305–320.

Zavadskas, E. K., Kaklauskas, A. and Vilutiene, T. (2009b) Multicriteria evaluation of apartment blocks maintenance contractors: Lithuanian case study, *International Journal of Strategic Property Management*, 13(4), pp. 319–338. doi:10.3846/1648-715X.2009.13.319-338

Zavadskas, E. K., Turskis, Z. and Tamošaitienė, J. (2010) Risk assessment of construction projects, *Journal of Civil Engineering and Management*, 16(1), pp. 33–46. doi:10.3846/jcem.2010.03

Zavadskas, E. K. and Turskis, Z. (2011) Multiple criteria decision making (MCDM) methods in economics: an overview, *Technological and Economic Development of Economy*, 17(2), pp. 397–427. doi:10.3846/20294913.2011.593291

SANTRAUKA

PRIEŽIŪROS STRATEGIJOS PARINKIMAS TAIKANT AHP IR COPRAS METODUS NEAPIBRĖŽTOSE SITUACIJOSE

Mohammad Majid FOULADGAR, Abdolreza YAZDANI-CHAMZINI, Ali LASHGARI, Edmundas Kazimieras ZAVADSKAS, Zenonas TURSKIS

Turto valdymas, kaip sistemingas veiklos procesas materialiajam turtui palaikyti ir atnaujinti, yra svarbus sprendimų priėmimo sandas, reikalingas sunkiajai įrangai valdyti ir naudoti. Pasirinkti priežiūros strategiją yra ypač svarbu projektuojant kasybą. Tačiau techninės priežiūros strategijos parinkimo pobūdis yra sudėtingas daugiatikslio sprendimų priėmimo (MCDM) uždavinys, apimantis tiek materialius, tiek nematerialius aspektus, tarpusavyje dažnai prieštaraujančius. Kai sprendimų priėmėjui kyla neaiškumų nustatant ir apibrėžiant rodiklių vertes ir svorius, neraiškiųjų aibių teorija yra tinkama priemonė esamam neapibrėžtumui aprašyti. Straipsnyje pateikiamas naujas neraiškusis MCDM būdas, pagrįstas COPRAS (kompleksinio proporcingo projektų įvertinimo) ir AHP (analitinio hierarchijų proceso) metodais, tikslingoms nekilnojamojo turto palaikymo strategijoms įvertinti. Rodiklių vertės ir svoriai yra apibrėžti lingvistinėmis sąvokomis. Neraiškusis AHP taikomas vertinimo rodiklių svoriams apskaičiuoti. Paskui alternatyvų rangai nustatyti taikant neraiškiųjų aibių teoriją ir COPRAS metodą. Naujai pasiūlytas modelis pritaikytas realiam uždaviniui spręsti.