Tunnelling and Underground Space Technology 48 (2015) 101–109

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Selection of an appropriate fan for an underground coal mine using the Analytic Hierarchy Process

Nilufer Kursunoglu, Mustafa Onder *

Eskisehir Osmangazi University, Mining Engineering Department, Eskisehir, Turkey

ARTICLE INFO

Article history:
Received 19 September 2014
Received in revised form 20 January 2015
Accepted 23 February 2015

Keywords:
Fan selection
Mine ventilation
Analytic Hierarchy Process (AHP)

ABSTRACT

Ventilation is a vital process in underground mining operations. Fans are typically used in these ventilation systems to supply airflow to mines. Sufficient ventilation systems provide adequate fresh air to underground mines to ensure a safe working environment. Thus, the selection of an appropriate fan is an important part of mine ventilation. Several parameters affect fan selection, so the fan selection process is complex and must be compliant with a set of options and criteria. In this study, the Analytic Hierarchy Process (AHP) method is used for this task, along with the Multi Criteria Decision Making (MCDM) method, to select a main fan for an underground coal mine in Turkey.

1. Introduction

Ventilation controls the air movement, amount, and direction in a confined space. Although it does not contribute directly to the production phase of an operation, the lack of proper ventilation will often cause lower worker efficiency, absenteeism, decreased productivity and increased accident rates. Air is necessary not only for breathing but also to disperse chemical and physical contaminants (e.g., gases, dusts, heat, and humidity) (MST, 1999). Mine ventilation systems are important components of underground mining systems. They provides a sufficient quantity of air to maintain a suitable working environment. A mine ventilation system should be very reliable and, thus, must be maintained regularly throughout the service life of the mine. In reality, failures of mine ventilation systems do occasionally happen, and such failures can result in potential risk to mine workers (Cheng et al., 2014). To ensure a safe and productive environment in an underground coal mine, a good ventilation system is mandatory. A good ventilation system should ensure that the regulatory requirements are met throughout the mine while also providing miners with sufficient fresh air and keeping operating costs to a minimum (Sasmito et al., 2013). Adequate airflow in underground mines is necessary to create a safe environment for mine workers and machinery. To create safe working conditions, the quantity and quality of airflow in a ventilation system must be adequate to dilute mine gases, to remove dust and to control the air temperature in the mine (Wempen, 2012). Fans play a major role in these ventilation systems and are one of the most important pieces of equipment in underground mines. Their performance plays an important role in the safety of staff and production. Ventilation fans provide airflow and pressure to properly circulate the air to the working faces in the mine. An inefficient fan can cause financial and operational problems. Thus, fan selection for mine ventilation is essential. Each type and size of fan has different characteristics, and a fan's performance curve is developed by the fan manufacturers. A fan's performance curve is a graphical presentation of the performance of a fan and includes the flow rate and pressure. Traditional selection methods of fans are based on the fan curve data provided by the manufacturers. In the traditional method, pressure and flow rate are used. However, other parameters influence fan selection; this conventional method is not sufficient to identify an appropriate fan. Gupta et al. (2000) listed the major criteria for fan selection. These criteria included the efficiency of the fan, initial and operating costs, maintenance and repair costs, level of sound emission by the fan and degree of permissible sound emission at the fan site, size and nature of the housing required by the fan, reliability of the fan, and facility of reversal of the air current. Hartman et al. (1997) stated that a working mine is not stationary but continually changing. Because a fan has a useful life of 15–25 years, an attempt is made to select a fan that will be suitable for the range of operating conditions that will be encountered in this period. The authors noted that the primary problem in selection is economical because many fans meet safety, noise-level, and size limitations. According to Evans (2003), energy efficiency and noise generation are functions of fan operation. Fan selection and sizing that recognizes fan efficiency parameters and other system affects can reduce

* Corresponding author.
E-mail address: monder@ogu.edu.tr (M. Onder).

http://dx.doi.org/10.1016/j.tust.2015.02.005
0886-7798/

operating costs and prevent generation of excessive low-frequency noise.

Fan selection is a function of many parameters; therefore, it can be considered to be a decision making process. This decision making process can be aided by the Multiple Criteria Decision Making (MCDM) method. The general objective of MCDM is to assist the decision maker in selecting the most suitable alternative from a number of feasible alternatives using multiple choice criteria and diverse criterion priorities. The problems of MCDM can be broadly classified into two categories: multiple attribute decision making (MADM) and multiple objective decision making (MODM); these methods are chosen in the cases of selection problems and design problems, respectively. MODM methods have decision variable values that are determined in a continuous or integer domain with an infinite or very large number of choices, the best of which should satisfy the decision maker's constraints and preference priorities. Conversely, MADM methods involve selecting from a finite number of alternatives (Rao, 2007).

Selecting the most appropriate fan is a multi-criterion and multi-objective decision bound by a set of constraints. One possible solution to consider the complexities encountered in this decision could be accomplished by the Analytic Hierarchy Process (AHP). The AHP is a systematic approach developed in the 1970s to make decisions based on experience, intuition and heuristics. This structure is a well-defined methodology derived from sound mathematical principles. Due to its simplicity and ease of use, the AHP has found acceptance among decision makers. This process helps in structuring the complexity, measurement and synthesis of rankings. These features make it suitable for a wide variety of applications (Bhushan and Rai, 2004).

In the literature, there are many applications of decision-making techniques in mining operations. Mohsen et al. (2010) used the AHP method to select a location for mineral processing in a Sangan iron ore mine. Jianqing (2011) established three hierarchy evaluation models for evaluating the status of a mine gas prevention system, structured a judgment matrix of every hierarchy, and established a computer program to calculate the weight of every evaluation factor and consistency checks. Lashgari et al. (2012) used a hybrid model of fuzzy AHP and the Analytic Network Process to assign weights to the parameters. Then, the necessary loading and hauling equipment of the Gole Gohar surface mine were selected using the TOPSIS method. Zoran et al. (2011) used the AHP method in the process of selecting a transportation system in a lead and zinc mine during its planning phase. Adebimpe et al. (2013) selected mine equipment for the Ajabanoko iron ore deposit by using TOPSIS and AHP. Owusu-Mensah and Musingwini (2011) used AHP to select the best ore transport system for the underground mine at AngloGold Ashanti's Obuasi mine.

The main objective of this study is to select an appropriate fan for an underground coal mine using AHP. Decision-making criteria of the study that can be effective for the selection process were defined from the literature. After determining alternative fans according to the traditional selection process from the manufacturers' catalogues, the most appropriate fan was selected using an AHP algorithm.

2. The Analytic Hierarchy Process

AHP is a multi-criteria decision making (MCDM) method that helps a decision-maker facing a complex problem with multiple conflicting and subjective criteria (e.g., location or investment selection, projects ranking, etc.) (Ishizaka and Labib, 2009). It is a theory of measurement through pairwise comparisons and relies on the judgments of experts to derive priority scales. It is these scales that measure intangibles in relative terms. The comparisons are made using a scale of absolute judgments that represents how much one element dominates another with respect to a given attribute (Saaty, 2008). The AHP focuses on breaking a problem down and then aggregating the solutions of all the subproblems into a conclusion. It facilitates decision making by organizing perceptions, feelings, judgments, and memories into a framework that exhibits the forces that influence a decision. In the simple and most common case, the forces are arranged from the more general and less controllable to the more specific and controllable (Saaty, 1999).

In the first step of the AHP, a decision-making problem is decomposed into a hierarchical structure with decision elements (e.g., objective, criteria, sub-criteria, alternatives). The decomposition is performed from the top to the bottom, from the objective to the criteria and sub-criteria to the final alternatives.

A judgment matrix is formed according to a decision maker's judgment and used to compute the priorities of the elements. The comparison matrix is expressed as shown below:

$$A = \begin{bmatrix} 1 & w_1/w_2 & \dots & w_1/w_n \\ w_1/w_2 & 1 & \dots & w_2/w_n \\ \dots & \dots & \dots & \dots \\ w_n/w_1 & w_n/w_2 & \dots & 1 \end{bmatrix} \quad (1)$$

where w_1 is the weight of element 1, w_2 is the weight of element 2 and w_n is the weight of element n. The relative importance of two elements is rated using Saaty's 9-point scale (Table 1).

In a pair-wise comparison matrix that will be formed based on the numerical value of criteria, own value of the criteria is used directly. For minimization and maximization problems, pair-wise comparison matrices are constructed as below (Sipahioglu, 2008):

$$A = \begin{bmatrix} 1 & w_2/w_1 & \dots & w_n/w_1 \\ w_1/w_2 & 1 & \dots & w_n/w_2 \\ \dots & \dots & \dots & \dots \\ w_1/w_n & w_2/w_n & \dots & 1 \end{bmatrix} \quad \text{(For minimization problems)} \quad (2)$$

Table 1
Fundamental scale of absolute numbers (Saaty, 2008).

Intensity of importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it compared to activity j, then j has the reciprocal value when compared with i	
1.1–1.9	If the activities are very close	May be difficult to assign the best value; compared to other contrasting activities, the size of the small numbers would not be noticeable, yet they can still indicate the relative importance of the activities

$$A = \begin{bmatrix} 1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & 1 & \dots & w_2/w_n \\ \dots & \dots & \dots & \dots \\ w_n/w_1 & w_n/w_2 & \dots & 1 \end{bmatrix} \quad \text{(For maximization problems)} \tag{3}$$

The eigenvector method is used to calculate the relative weights of the elements in each pairwise comparison matrix. The relative weights of matrix A are obtained from the following equation:

$$(A - \lambda_{\max} \times I) \times w = 0 \tag{4}$$

where $\lambda_{\max}$ is the largest eigenvalue of matrix A.

Saaty (1990) suggested utilizing the Consistency Index (CI) and the Consistency Ratio (CR) to verify the consistency of the comparison matrix. CI and CR are defined as follows:

$$CI = (\lambda_{\max} - n)/(n - 1) \tag{5}$$

where n is the size of the matrix.

$$CR = CI/RI \tag{6}$$

where RI represents Saaty's calculated random index measures for various sizes of matrix size (n). If the CR value is less than or equal to 0.10, comparisons made by a decision maker are considered acceptable. Larger values of CR require revision of the judgments of the decision maker.

Local priorities of the elements of different levels are aggregated to obtain the final priorities of the alternatives in the last step of the AHP.

3. Ventilation system of the underground coal mine

An underground mine area is located in the north of Turkey in the Zonguldak Coal Basin. The stream of airflow intakes and returns is shown in Fig. 1.

The airways' geometric properties, related friction factors (McPherson, 1993) and equivalent lengths for various sources of shock loss (Hartman et al., 1997) were used to calculate the resistance of the airways. Airway descriptions and specifications are given in Table 2. Atkinson's equation is given as follows (McPherson, 1993):

$$R = k(L + L_{eq})\frac{per}{A^3} \tag{7}$$

According to the information given above, the air resistance of the mine is calculated to be 0.448 N s^2/m^8. Full mechanized retreat longwall panel will be applied in this mine. Approximately ten

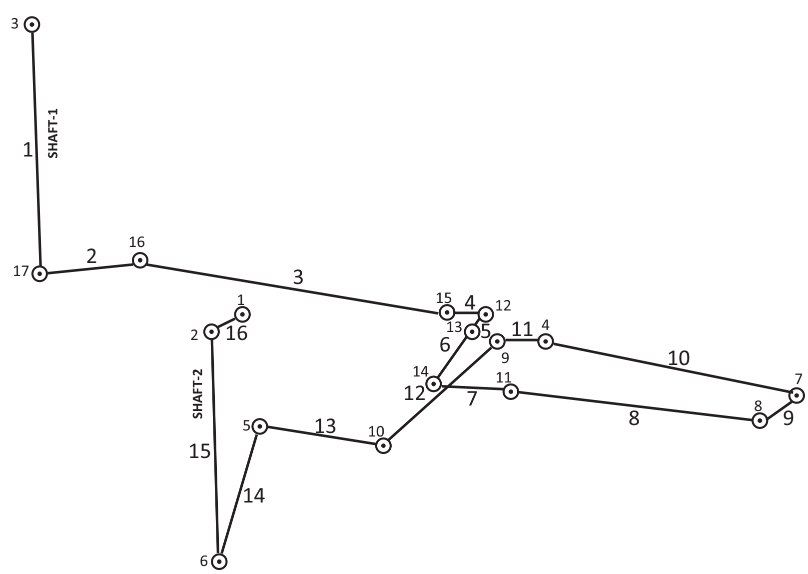

Fig. 1. Ventilation network layout.

Table 2
Airway descriptions and specifications of the ventilation network layout.

Branch No	From	To	Airway description	Length ($L + L_{eq}$) (m)	Area (m^2)	Perimeter (m)	k Factor (kg/m^3)	Resistance (N s^2/m^8)
1	3	17	SHAFT – 1	749.80	50.27	25.13	0.0065	0.00096
2	17	16	−510 gallery – part – 1	262.80	23.95	19.03	0.0400	0.01456
3	16	15	−510 gallery – part – 2	874.90	23.95	19.03	0.0100	0.01212
4	15	12	−510/−500 incline	86.60	23.95	19.03	0.0400	0.00480
5	12	13	−500 gallery – part – 1	37.00	23.95	19.03	0.0400	0.00205
6	13	14	−500 gallery – part – 2	571.10	23.95	19.03	0.0400	0.03164
7	14	11	Intake Airway	226.90	19.64	17.35	0.0100	0.00520
8	11	8	Maingate	719.40	19.64	17.35	0.0100	0.01648
9	8	7	Faceline	185.30	9.00	16.00	0.0500	0.20335
10	7	4	Tailgate	737.50	19.64	17.35	0.0100	0.01689
11	4	9	Return Airway	278.30	19.64	17.35	0.0100	0.00637
12	9	10	−460 gallery	939.10	23.95	19.03	0.0400	0.05203
13	10	5	−460/−410 incline	282.80	23.95	19.03	0.0400	0.01567
14	5	6	−410 gallery	1113.10	23.95	19.03	0.0400	0.06168
15	6	2	SHAFT – 2	624.40	50.27	25.13	0.0046	0.00057
16	2	1	Ventilation Drift	71.00	23.95	19.03	0.0400	0.00385

employees work in a full mechanized longwall panel. Electrical equipment source heat value can be calculated as below (McPherson, 1993);

$$\Delta\theta_d = (\theta_{d,2} - \theta_{d,1}) = \left[\frac{u_1^2 - u_2^2}{2} + (Z_1 - Z_2)g + \frac{\sum q_{sen}}{M}\right]\frac{1}{C_{pa}}\,^\circ\mathrm{C} \tag{8}$$

where

θ_d = dry bulb temperature (°C).
u = air velocity (m/s).
Z = height above datum (m).
g = gravitational acceleration (m/s^2).
q_{sen} = sensible heat transfer (W/m^2).
M = mass flow of air (kg/s).
C_{pa} = specific heat for dry air (1005 J/kg °C).

The average motor power of full mechanized equipment used under these conditions is taken to be 150 kW and from the above equation, additional heat value to the mine air is approximately 2 °C. Climatic condition is not problem for underground coal mines in Turkey. The amount of the required air for ten employees is a low value. Therefore, local conditions are essential in calculation of the required airflow (McPherson, 1993). Thus, it is more appropriate to calculate the required airflow according to the methane rate.

The *required airflow* is calculated according to the *production rate* and *gas emission rate*. The longwall panel length is 700 m, the panel width is 150 m, the face width is 4 m, the cutting height is 1.5 m, the advance rate is 5 m/day, and the average specific gravity of excavated coal is 1.65 m^3/t. Using this information, the *production rate* is computed to be 1856.25 t/day. Based on the information obtained from the underground mine company, the *anticipated gas emission* is 16 m^3/t, and the *working hours per day* is 18. *The gas emission rate* at the given production rate is calculated to be $(1856.25 \times 16)/(3600 \times 18) = 0.46\ m^3/s$.

The required airflow is calculated using the following equation (McPherson, 1993) and found to be 45.83 m^3/s:

$$Q = \frac{100E_g}{C_g} \tag{9}$$

where Q is the required airflow (m^3/s), E_g is the gas emission rate (m^3/s) and C_g is the general body concentration to which gas is to be diluted in percentage by volume. The value of C_g is %1 in the formula above.

4. Application of Analytic Hierarchy Process

An exhaust fan will be used to ventilate the underground coal mine. For this purpose, three different fans that were feasible and appropriate to this mine were considered. These fans are identified as Fan 1, Fan 2 and Fan 3. The AHP methodology was used to compare the fans with the aim of installing a fan into Shaft-2 of the coal mine.

4.1. Development of the AHP model

To formulate the AHP model, it is necessary to identify the factors that influence the selection of an appropriate fan. Four main criteria were identified as important in selecting the most appropriate fan, *Technical*, *Operational*, *Environmental* and *Economical*, each with specific sub-criteria. The main criteria and sub-criteria for the selection are summarized in Table 3.

The first step in developing the AHP model is to develop with a hierarchical structure of the decision-making problem. This classifies the objective, all decision criteria and variables into three major levels. The top level represents the main objective of selecting a fan. Level 2 represents the main criteria and sub-criteria. Level 3 contains the decision alternatives that affect the selection process. Fig. 2 depicts the hierarchy of the AHP model for the choice an appropriate fan.

Table 3
Criteria and sub-criteria used in the AHP model.

Criteria	Sub-criteria	Description
Technical (C_1)	Air quantity (SC_1)	Comprises the amount of air transferred by a fan per unit time
	Pressure (SC_2)	Comprises the pressure affecting on unit area during air transfer by the fan
	Air power (SC_3)	Comprises the amount of electric power required for the operation of the fan under certain conditions
	Efficiency (SC_4)	Comprises the amount of air moved per unit of electrical energy input to the fan motor
Operational (C_2)	Productivity (SC_5)	An efficient fan consumes less energy while performing the desired performance. It comprises providing efficient energy consumption of the fan
	Safety (SC_6)	Comprises increased friction and is made of spark-preventing materials; has a motor that can work with a risk of fire and higher temperatures
	Flexibility (SC_7)	Comprises adaption to changes in production conditions of the fan as rapid temperature changes, pressure changes, etc
Environmental (C_3)	Noise level (SC_8)	Comprises the working acceptable sound level (dB) of the fan
	Vibration (SC_9)	One of the most common causes of fan down time is vibration. A fan's environment continually induces vibration
Economical (C_4)	Operating cost (SC_{10})	In many instances, the cost of energy consumption over the life of a fan is significantly more than the initial capital cost of the equipment. Many factors affect the cost of energy. In some instances, the mine pays not only an energy cost (cost per kW h) but also a demand cost (cost per installed kW). In these instances, costs of operations tend to be significant and can be a major determining factor in the selection of a fan (CEMI, 2012)

4.2. Identification of the alternatives

In the process of deciding on a fan selection, each alternative is evaluated by examining the manufacturer catalogues according to mine requirements, which are discussed in Section 3. The required air flow for the mine is 45.83 m^3/s. Considering leakages and a safety factor, three alternative fans were determined to provide 60 m^3/s of air for the underground coal mine. The technical characteristics of the three fan alternatives are given in Table 4.

In ventilation systems with a single main fan, the system operating point (OP) is defined by the intersection of the mine

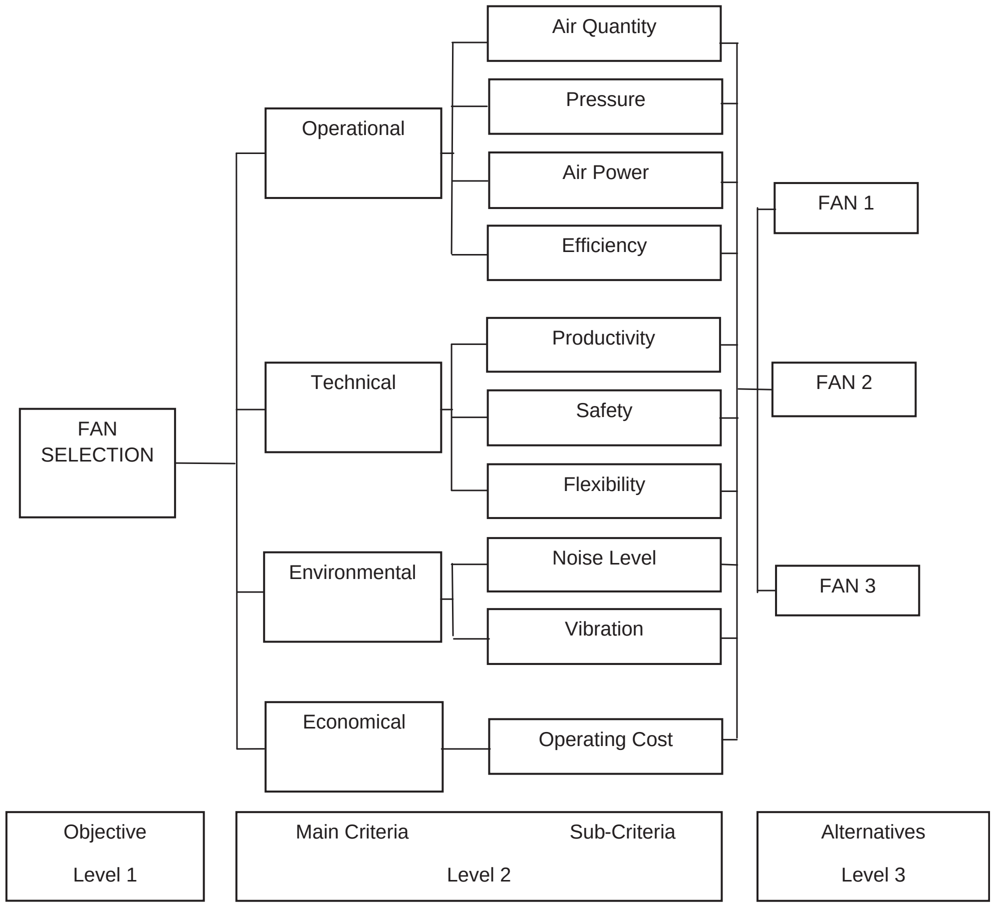

Fig. 2. Hierarchical structure to select the appropriate fan.

Table 4
Technical characteristics of the alternative fans.

	Fan 1	Fan 2	Fan 3
Pressure (Pa)	5500	3820	5400
Air quantity (m^3/s)	64.8	64	65
Air power (kW)	356.4	340	630
Efficiency (%)	75	76	90
Noise level (dB)	93	127	96
Operating cost ($/year)	778.434	526.957	638.866

characteristic curve, based on Atkinson's equation, and the fan characteristic curve. As mining progresses, the total resistance is increased, the mine characteristic curve becomes steeper, and the operating point moves up the fan curve, reducing the total air quantity and increasing the system pressure. Different resistance curves are plotted on the fan curves to show the fan's actual operating point. For the "*OP2*" where the two curves (Fan 2 and $R = 0.9$ N s^2/m^8) intersect, air flow 64 m^3/s is delivered against pressure approximately 3800 Pa (McPherson, 1993). This concept is illustrated in Fig. 3.

Annual operating costs for the fans are calculated according to the equation below (McPherson,1993). Electrical power charges are normally quoted in cost per kilowatt-hour. Hence, the cost of operating a fan for 24 h per day over 365 days in year is as follows:

$$S_o = \frac{p_{ft}Q}{1000\eta} e \times 24 \times 365 \tag{10}$$

where e is the cost of power ($ per kW h), p_{ft} is the fan pressure, Q is airflow and η is efficiency. Electrical power is assumed to cost $ 0.187 per kW h.

4.3. Pair-wise comparisons

The fundamental goal of this study was to define which underground mine fan was most compatible. To reach this objective, the fan selection problem was decomposed into a hierarchical structure (Fig. 2). Pair-wise comparison matrices were formed for the numerical and non-numerical values of the criteria by the experts who worked for the underground coal mine. Saaty's nine-point scale shown in Table 1 was utilized for non-numerical criteria. However, the numerical criteria SC_1, SC_2, SC_3, SC_4, SC_8 and SC_{10} were used in the comparison matrices according to matrix of maximization and minimization problems as shown in Section 2. The goals of the analysis were to maximize SC_1 and minimize SC_2, SC_3, SC_4, SC_8 and SC_{10}.

To develop the comparison between the final alternatives, it is necessary to give specific weights to each main criterion; the weight is obtained by filling in the pair-wise comparison matrix for the main criteria (Table 5). The principal diagonal of the matrix is always equal to 1. Because each criteria is compared to itself and the value corresponds to 1. The pair-wise comparison matrices are reciprocal (in assigning a value from 1 to 9 to the comparison matrix between the criteria i and j, the reciprocal value corresponds to the comparison between j and i). Firstly, a questionnaire form was presented to the expert team of the mine to collect their opinions. The comparison of the two criteria C_i and C_j was made using question: "of the two criteria C_i and C_j, which is the most important and how much more?". Expert team's answers were entered into the matrix table. Table 5 is then normalized by dividing each entry in a column by the sum of all the entries in that column, so that they add up to one. Following normalization, the weights are averaged across the rows to give an average weight

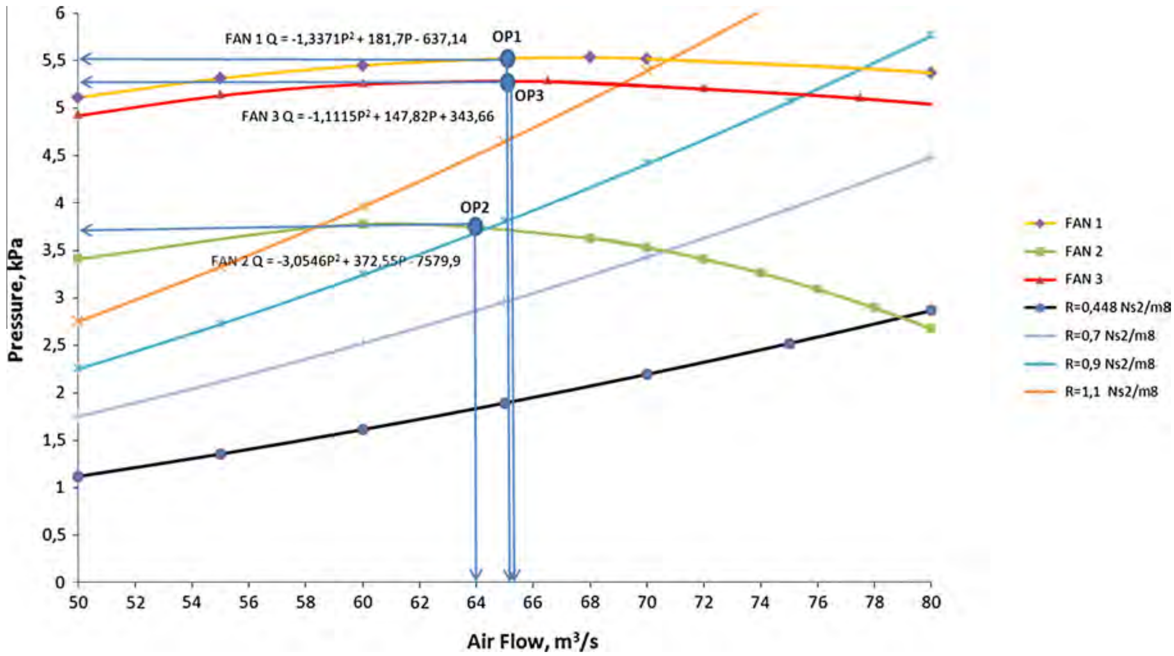

Fig. 3. Interaction between fan operating curves and mine characteristic curves.

Table 5
Pair-wise comparison matrix for the main criteria.

Fan selection	C_1	C_2	C_3	C_4
C_1	1	4	7	3
C_2	1/4	1	3	2
C_3	1/7	1/3	1	1/2
C_4	1/3	1/2	2	1
Total	1.73	5.83	13.00	6.50

for each main criterion, as shown in Table 6. Calculation of λ_{max}, *CR* and *CI* was performed with reference to the theoretical explanation given in Section 2. Similar steps were repeated for normalizing and determining of priorities of the other pair-wise comparison matrices, which were established for fan selection. *CR* values of pair-wise comparison matrices vary between 0 and 0.10 in the study. It could be concluded that all comparisons were consistent.

From the results summarized in Table 6, it is apparent that the *Technical* main criterion is the most important factor (priority value: 0.5663), followed by the *Operational*, *Economical* and *Environmental* main criteria, respectively.

Tables 7–9 illustrate the priority values of each sub-criterion. *Air Quantity* (SC_1) is the most important sub-criterion with a score of 0.6761 in the *Technical* main criterion; *Productivity* (SC_5) is the most important sub-criteria with a score of 0.6555 in the *Operational* main criterion; *Noise Level* (SC_8) is the most important sub-criteria with a score of 0.7500 in the *Environmental* main criterion.

Alternatives were compared pairwise with respect to each of the sub-criteria. Tables 10–13 show the expert team's comparison of alternatives against each of the non-numerical sub-criteria (SC_5, SC_6, SC_7 and SC_9).

The weights of each sub-criterion from the three matrices (Tables 7–9) and the weights of the alternatives with reference

Table 7
Comparison of sub-criteria with respect to the "technical" criteria.

Technical	SC_1	SC_2	SC_3	SC_4	Local priorities	
SC_1	1	7	8	7	0.6761	$\lambda_{max} = 4.1911$
SC_2	1/7	1	2	4	0.1688	CR = 0.0637
SC_3	1/8	1/2	1	2	0.0939	CI = 0.0708 $\leqslant$ 0.1
SC_4	1/7	1/4	1/2	1	0.0612	

Table 8
Comparison of sub-criteria with respect to the "operational" criteria.

Operational	SC_5	SC_6	SC_7	Local priorities	
SC_5	1	3	5	0.6555	$\lambda_{max} = 3.0292$
SC_6	1/3	1	1	0.1867	CR = 0.0146
SC_7	1/5	1	1	0.1578	CI = 0.0252 $\leqslant$ 0.1

Table 9
Comparison of sub-criteria with respect to the "environmental" criteria.

Environmental	SC_8	SC_9	Local priorities	
SC_8	1	3	0.7500	$\lambda_{max} = 2.000$
SC_9	1/3	1	0.2500	CR = 0
				CI = 0 $\leqslant$ 0.1

Table 6
Normalized pair-wise comparison matrix according to main criteria.

Fan selection	C_1	C_2	C_3	C_4	Local priorities	
C_1	0.5793	0.6857	0.5385	0.4615	0.5663	$\lambda_{max} = 4.0868$
C_2	0.1448	0.1714	0.2308	0.3077	0.2137	CR = 0.0289
C_3	0.0828	0.0571	0.0769	0.0769	0.0734	CI = 0.0322 $\leqslant$ 0.1
C_4	0.1931	0.0857	0.1538	0.1538	0.1466	

Table 10
Comparisons of the alternatives with respect to "productivity" sub-criteria.

	Fan 1	Fan 2	Fan 3	Local priorities	
Fan 1	1	1/2	5	0.3661	λ_{max} = 3.0948
Fan 2	2	1	4	0.5321	CR = 0.0474
Fan 3	1/5	1/4	1	0.1018	CI = 0.0817 $\leqslant$ 0.1

Table 11
Comparisons of the alternatives with respect to "safety" sub-criteria.

	Fan 1	Fan 2	Fan 3	Local priorities	
Fan 1	1	7	4	0.7014	λ_{max} = 3.0326
Fan 2	1/7	1	1/3	0.0853	CR = 0.0163
Fan 3	1/4	3	1	0.2133	CI = 0.0281 $\leqslant$ 0.1

Table 12
Comparisons of the alternatives with respect to "flexibility" sub-criteria.

	Fan 1	Fan 2	Fan 3	Local priorities	
Fan 1	1	5	9	0.7482	λ_{max} = 3.0293
Fan 2	1/5	1	3	0.1804	CR = 0.0146
Fan 3	1/9	1/3	1	0.0714	CI = 0.0252 $\leqslant$ 0.1

Table 13
Comparisons of the alternatives with respect to "vibration" sub-criteria.

	Fan 1	Fan 2	Fan 3	Local priorities	
Fan 1	1	9	2	0.6153	λ_{max} = 3.0012
Fan 2	1/9	1	1/5	0.0660	CR = 0.0006
Fan 3	1/2	5	1	0.3187	CI = 0.0011 $\leqslant$ 0.1

Table 14
Final priorities of the three fans.

Alternatives	Main criteria weights				AHP results
	C_1 0.5663	C_2 0.2137	C_3 0.0734	C_4 0.1466	
Fan 1	0.3325	0.4890	0.4315	0.2706	0.3641
Fan 2	0.3526	0.3932	0.2198	0.3997	0.3585
Fan 3	0.3149	0.1178	0.3487	0.3297	0.2774

to the sub-criteria are multiplied to obtain the priorities of the alternatives on the basis of the main criteria. For example, the rating of Fan 1 with regard to the *Operational* main criterion can be calculated as follows:

$(0.6555 \times 0.3661) + (0.1867 \times 0.7014) + (0.1578 \times 0.7482) = 0.4890.$

This outcome is shown in Table 14. The overall weights of the three fans were obtained by multiplying the priority of each main criterion in Table 6 by the priority of each alternative.

The overall ranking of the alternatives can be calculated as:

$(0.5663 \times 0.3325) + (0.2137 \times 0.4890) + (0.0734 \times 0.4315) + (0.1466 \times 0.2706) = 0.3641$ (Fan 1).
$(0.5663 \times 0.3526) + (0.2137 \times 0.3932) + (0.0734 \times 0.2198) + (0.1466 \times 0.3997) = 0.3585$ (Fan 2).
$(0.5663 \times 0.3149) + (0.2137 \times 0.1178) + (0.0734 \times 0.3487) + (0.1466 \times 0.3297) = 0.2774$ (Fan 3).

It is concluded from Table 14 that Fan 1, with a rating of 0.3641, is the most preferred, followed by Fan 2 and Fan 3. The percentage priorities of Fan 1, Fan 2 and Fan 3 are 36.41%, 35.85% and 27.74%, respectively.

The performance graph (Fig. 4) depicts the priorities of the final alternatives with regard to the main criteria. If the *Technical and Economical* main criteria are considered, Fan 2 is preferable to Fan 1 and Fan 3. If the *Operational and Environmental* main criteria are considered, Fan 1 is preferable to Fan 2 and Fan 3.

5. Sensitivity analysis

At the end of the evaluation process, a sensitivity analysis can be applied by decision makers to analyze the elasticity of the final decision. The final priorities of the alternatives are highly dependent on the priority weights assigned to the main criteria; thus, changing the main criteria priority values (i.e., either increasing

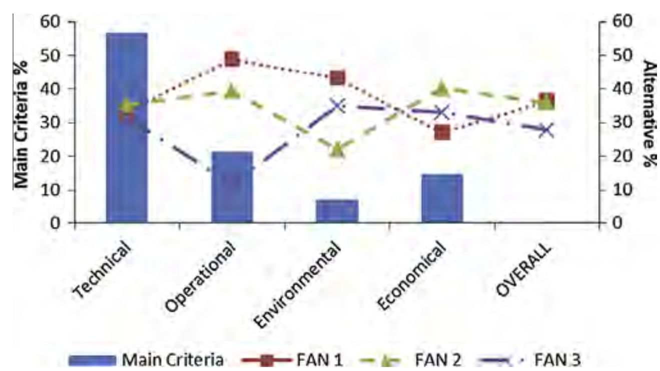

Fig. 4. Performance graph of the fans considered.

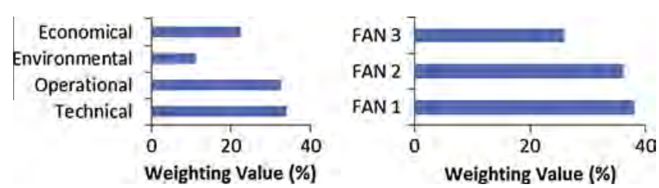

Fig. 5a. Sensitivity of alternatives when measurement (C_1) is decreased by 40%.

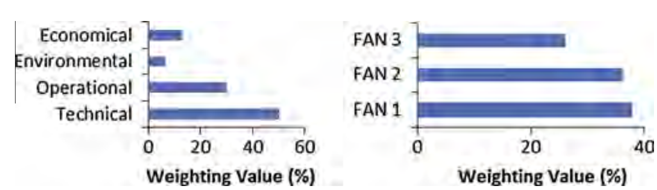

Fig. 5b. Sensitivity of alternatives when measurement (C_2) is increased by 40%.

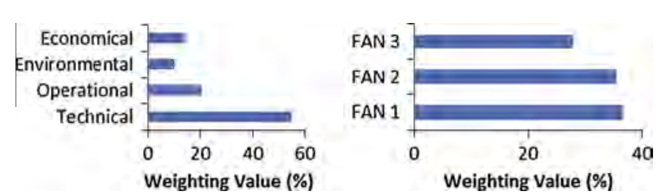

Fig. 5c. Sensitivity of alternatives when measurement (C_3) is increased by 40%.

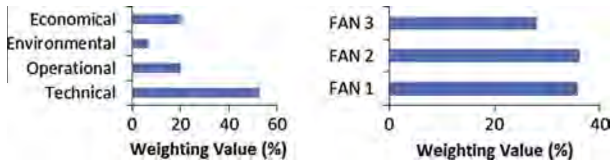

Fig. 5d. Sensitivity of alternatives when measurement (C_4) is increased by 40%.

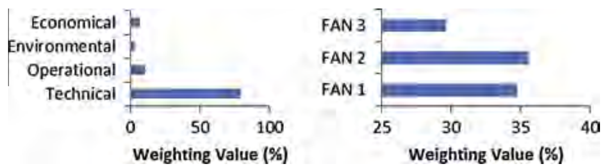

Fig. 5e. Sensitivity of alternatives when measurement (C_1) is increased by 40%.

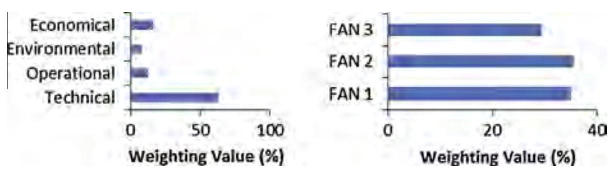

Fig. 5f. Sensitivity of alternatives when measurement (C_2) is decreased by 40%.

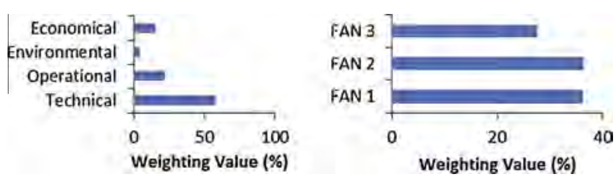

Fig. 5g. Sensitivity of alternatives when measurement (C_3) is decreased by 40%.

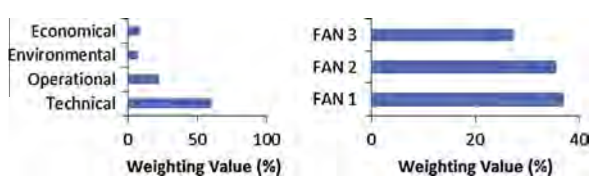

Fig. 5h. Sensitivity of alternatives when measurement (C_4) is decreased by 40%.

or decreasing it) will consequently alter the final decisions or ranks of the alternatives. A sensitivity analysis was carried out to observe the impact of the main criteria on the alternative fans.

The graphs in Fig. 5 show the relationships that exist between the three alternatives with respect to the weights of the main criteria. Eight scenarios were simulated, giving different values to the main criteria weights.

The results are summarized in Fig. 5: the left column shows the weights established for the main criteria in the eight considered scenarios, and the right column indicates the final priority of the three alternatives. Fig. 5a shows that decreasing the weight of the criteria of *Technical* by up to 40%. Figs. 5b–d shows that increasing the weight of the criteria of *Operational, Environmental* and *Economical* by 40%. Fig. 5e shows that increasing the weight of the criteria of *Technical* by up to 40%. Figs. 5f–h shows that decreasing the weight of the criteria of *Operational*, *Environmental* and *Economical* by 40%. By analyzing these results, it was confirmed that Fan 1 is the most suitable fan in the scenarios where the weight of the criteria *Operational*, *Environmental* are increased by 40% and the criteria *Technical*, *Economical* are decreased by 40%, Fan 2 is the most suitable fan in the scenarios where the weight of the criteria *Technical*, *Economical* are increased by 40% and the criteria *Operational*, *Environmental* are decreased by 40%. The results of this sensitivity analysis are summarized in Table 15.

6. Conclusions

This paper has demonstrated the application of the AHP technique in evaluating fan options for an underground coal mine in Turkey. Unlike the traditional method for the selection of fans, the AHP method makes it is possible to select the most appropriate fan in a more scientific manner that preserves integrity and objectivity. It is also a flexible method that can be applied with different evaluation criteria and alternatives in the fan selection process. The method is transparent, easy to comprehend and easy to apply by decision makers.

In the established AHP model, three alternatives (i.e., Fan 1, Fan 2 and Fan 3) were evaluated with regard to four main criteria and their sub-criteria. The evaluation revealed that the most suitable fan for the mine is Fan 1. The evaluation also revealed that the *Technical* main criterion carried the highest weight of relative importance in the selection process; this was a result of the fact that decision makers pay more attention to *Technical* and *Operational* criteria than the *Economical* criterion, which is considered to be the major determining factor in fan selection. The AHP results were also analyzed using sensitivity analyses. Fan 1 or Fan 2 can be selected as the most suitable according to the sensitivity analyses.

Table 15
Rank of alternative priorities obtained by simulating eight scenarios in a sensitivity analysis for each main criteria with respect to certain goal.

Rank	Technical Decreased by 40%		Operational Increased by 40%		Environmental Increased by 40%		Economical Increased by 40%	
	Alternatives	Priority value (%)	Alternatives	Priority value (%)	Alternatives	Priority value (%)	Alternatives	Priority value (%)
1	Fan 1	38.05	Fan 1	37.77	Fan 1	36.62	Fan 2	36.12
2	Fan 2	36.12	Fan 2	36.21	Fan 2	35.41	Fan 1	35.79
3	Fan 3	25.82	Fan 3	26.02	Fan 3	27.97	Fan 3	28.09
	Increased by 40%		Decreased by 40%		Decreased by 40%		Decreased by 40%	
1	Fan 2	35.57	Fan 2	35.48	Fan 2	36.28	Fan 1	37.03
2	Fan 1	34.77	Fan 1	35.06	Fan 1	36.20	Fan 2	35.58
3	Fan 3	29.66	Fan 3	29.46	Fan 3	27.51	Fan 3	27.39

Ventilation is a crucial task in mining operations. Selection of a suitable fan for an underground mine requires the consideration of a numerous criteria, including technical, operational, environmental and economical factors. This selection problem is based on the comparisons of alternative fans according to the identified criteria. Therefore, it is necessary to use a decision-making method that considers multiple criteria to solve the problem. For this purpose, in this study, AHP, a powerful and flexible tool that is used to solve multiple-criterion problems, was applied as the selection procedure, and a suitable fan was selected.

References

Adebimpe, R.A., Akande, J.M., Arum, C., 2013. Mine equipment selection for Ajabanoko iron ore deposit, Kogi State, Nigeria. Sci. Res. 1 (2), 25–30.

Bhushan, N., Rai, K., 2004. The analytic hierarchy process. Strategic decision making. In: Applying the Analytic Hierarchy Process. Springer, pp. 11–15.

Centre for Excellence in Mining Innovation (CEMI), 2012. Ventilation Fan Specifications <https://www.minewiki.org/index.php/Ventilation_Fan_Specifications> (accessed 5.12.13).

Cheng, J., Zhou, F., Yang, S., 2014. Reliability allocation model and application in designing a mine ventilation system. Iranian J. Sci. Technol. 38, 61–73

Evans, J.B., 2003. Fan selection and sizing to reduce inefficiency and low frequency noise generation. Fan Noise 2003 International Symposium. pp. 1–7.

Gupta, S., Nath, R., Bhatttacharya, J., 2000. Application of fuzzy set theory for selection of mine fan. Mine Environ. Ventil., 249–254

Hartman, H.L., Ramani, R.V., Mutmansky, J.M., Wang, Y.J., 1997. Mine Ventilation. Mine Ventil. Air Condition., 162–389

Ishizaka, A., Labib, A., 2009. Analytic hierarchy process and Expert Choice: benefits and limitations. ORInsight 22 (4), 201–220.

Jianqing, Z., 2011. The application of analytic hierarchy process in mine gas prevention system. Procedia Eng. 26, 1576–1584.

Lashgari, A., Yazdani-Chamzini, A., Fouladgar, M.M., Zavadskas, E.K., Shafiee, S., Abbate, N., 2012. Equipment selection using fuzzy multi criteria decision making model: key study of Gole Gohar Iron Mine. Inzinerine Ekonomika-Eng. Econom. 23 (2), 125–136.

McPherson, M.J., 1993. Subsurface Ventilation Environmental and Engineering. Chapman & Hall.

Mohsen, S., Mohammad, A., Reza, K., Mohammad, K., 2010. Mineral processing plant location using the analytic hierarchy process – a case study: the Sangan iron ore mine (phase 1). Min. Sci. Technol. 20, 691–695.

Missouri University of Science and Technology (MST), 1999. Mine Ventilation Systems <http://web.mst.edu/~tien/218/lab8-systems.pdf> (accessed 15.04.14).

Owusu-Mensah, F., Musingwini, C., 2011. Evaluation of ore transport options from Kwesi Mensah Shaft to the mill at the Obuasi mine. Int. J. Min., Reclamat. Environ. 25, 109–125.

Rao, R.V., 2007. Introduction to Multiple Attribute Decision-making (MADM) Methods. Decision making in the manufacturing environment. <http://link.springer.com/chapter/10.1007%2F978-1-84628-819-7_3> (accessed 10.03.14).

Saaty, T.L., 1990. How to make a decision: the analytic hierarchy process. Eur. J. Oper. Res. 48 (1), 9–26.

Saaty, T.L., 1999. Basic theory of the analytic hierarchy process: how to make a decision. Rev. R. Acad. Cienc. Exact. Fis. Nat. 93, 406–407.

Saaty, T.L., 2008. Decision making with the analytic hierarchy process. Int. J. Services Sci. 1, 83–86.

Sasmito, A.P., Birgersson, E., Ly, H.C., Mujumdar, A.S., 2013. Some approaches to improve ventilation system in underground coal mines environment – a computational fluid dynamic study. Tunnell. Underground Space Technol. 34, 82–95.

Sipahioglu, A., 2008. Analytical Hierachy Process, Eskisehir Osmangazi University. Unpublished lecture notes.

Wempen, J.M., 2012. Characterization of air recirculation in multiple fan ventilation systems. Master Sci., 1–3, Chapter 1

Zoran, D., Saša, M., Dragi, P., 2011. Application of the AHP method for selection of a transportation system in mine planning. Underground Min. Eng. Faculty Min. Geol., Belgrade 19, 93–99.