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USING AN INTEGRATED MODEL FOR SHAFT SINKING METHOD SELECTION

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Abstract. Shafts have critical importance in deep mines and underground constructions. There are several traditional and mechanized methods for shaft sinking operations. Using mechanized excavation technique is an applicable alternative to improve project performance, although impose a huge capital cost. There are a number of key parameters for this selection which often are in conflict with each other and decision maker should seek a balance between these parameters. Therefore, shaft sinking method selection is a multi criteria decision making problem. This paper intends to use the combination of analytical hierarchy process and TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) methods under fuzzy environment in order to select a proper shaft sinking method. A real world application is conducted to illustrate the utilization of the model for the shaft sinking problem in Parvadeh Coal Mine. The results show that using raise boring machine is selected as the most appropriate shaft sinking method for this mine.

Keywords: shaft sinking, raise boring machine, shaft boring machine, MCDM, Fuzzy AHP, Fuzzy TOPSIS.

1. Introduction

Shaft is one of the most important capital openings of underground deep mines, which is used to have access to the ore body, as well as providing all services for underground operations including water supply, drainage, ventilation, personnel and ore transportation, communications and power. Shaft sinking operation may consume up to 60% of time of the underground mine development stage (Unrug 1992). This time depends on the selected sinking method and the depth of the underground mine (Hustrulid 1982). Therefore, selection of a proper method to sink the shafts is an important issue to minimize the development time and cost and assure success of the stage of development openings.

A number of technical issues should be concerned for the design of the shaft such as the approximate shaft location and underground space outline including a description of the characteristics of the shaft and its functions; the shaft capacity, diameter, hoisting depth and gear, shaft lining type, number of shaft insets, the main pipelines and cables, the quantity of airflow through the shaft and the depth of the shaft sump along with cost specifications (Read, Napierf 1994; Lin 2010). A preliminary evaluation of the hoisting depths and shaft diameter are needed beyond the initial phase of the project. Taking a view of over-designing is a good idea in this phase, to prevent facing a bottleneck and requiring the sinking of another shaft in case of potential increase of production (Hustrulid 1982).

In addition to the technical parameters, the safety and economic issues are also important to make the accurate decisions regarding the design and sinking the shafts (Bhulose 2004; Medineckienė *et al*. 2010). The costs associated with the shaft sinking operation can divided into two different categories; capital and operating costs. Capital costs are those costs that have accrued or accrue just to have the potential of using the required equipment and facilities and the use of piece of these equipment and facilities generate a constant stream of operating costs (Vorster 1980).

Many different methods can be applied to sink the shafts of the underground mines. To select the best alternative, different issues affecting the selection of the shaft sinking method should be considered and all possible options should be evaluated. Some of these criteria are quantitative and some are qualitative which need to be made quantified. Apart from selecting the most efficient shaft sinking method, decision maker should have enough knowledge and expertise of use it. As a result, it is complicated to consider all associated parameters simultaneously.

In traditional approaches of shaft sinking method selection, some critical factors such as safety are not taken into account. Moreover, the importance weights of different criteria are considered as equal. Moreover in these approaches the merits of mechanized boring systems such as rapid excavation, safety and performance of operations and simultaneous installation of rock supports are not considered.

In this paper, an applicable approach based on Multi Criteria Decision Making (MCDM) techniques including Fuzzy analytical hierarchy process (FAHP) and Fuzzy TOPSIS (FTOPSIS) for selection of shaft sinking method is introduced. TOPSIS method is utilized because of being rational, simple computations, and results are obtained in shorter time than other methods (Perçin 2009). However, TOPSIS is often criticized for its inability to deal with vague and uncertain problems (Yu *et al*. 2011). On the other hand, fuzzy sets are able to model the uncertainty. Moreover, Fuzzy AHP is widely used for solving MCDM problems in real issues (Karimi *et al.* 2011). Thus, FAHP, and FTOPSIS are combined to rank shaft sinking methods which applies FAHP to obtain criteria weights and FTOPSIS to acquire the final ranking order of shaft sinking methods.

As a field study, this approach is applied to select the best method for shaft sinking operation in Parvadeh Coal Mine, located in coal zone of Tabas which is the major collieries in central part of Iran and the largest Iranian coal mine. This is a semi-mechanized coal mine which both traditional and new shaft sinking methods are applicable there.

2. Shaft sinking methods

Shaft sinking methods can be divided into mechanized and conventional methods. Nowadays, the mechanization of underground mining and construction development is becoming increasingly significant with increased stress on efficient and safe operation (Douglas, Pfutzenruter 1989). Mechanized excavation is one of the alternatives to improve overall mine performance; since more process phases can take place simultaneously, e.g. excavation and muck removal. In some cases, the installation of rock support can also be performed simultaneously (Puhakka 1997).

On one hand, the conventional methods such as drilling and blasting and Alimak have been broadly utilized, so far have been used to drive more shafts and raises than any other system; in all kinds of rock, pilot and full-face, vertical and inclined, and even for raise and vein mining (Hustrulid 1982). On the other hand, the new mechanized systems such as rotary drilling method of boring large diameter holes by using Raise Boring Machine (RBM) and Shaft Boring Machine (SBM) for the mining and construction industries has proven to be extremely safe and economical (Robbins 2000).

Raise Boring Machine (RBM) is an automated boring machine which has been generally used in the underground mining and construction development since 1968 for boring shafts up to 1260 m in length and ranging from 0.7 m in diameter to 7.1 m. RBMs can be used in various types of operations including conventional raise boring, down boring, blind hole boring, pilot hole boring and horizontal boring (Breeds, Conway 1992). The RBM installs on top of the planned raise and bores a pilot hole, breaking through at the target point at the level below. The pilot bit is then replaced by a reamer head, with the diameter of the planned raise. The RBM pulls the reamer head upward, with strong force, while rotating, to break a circular hole in rock (Ozdemir 1986). Fig. 1 shows these various types of operations.

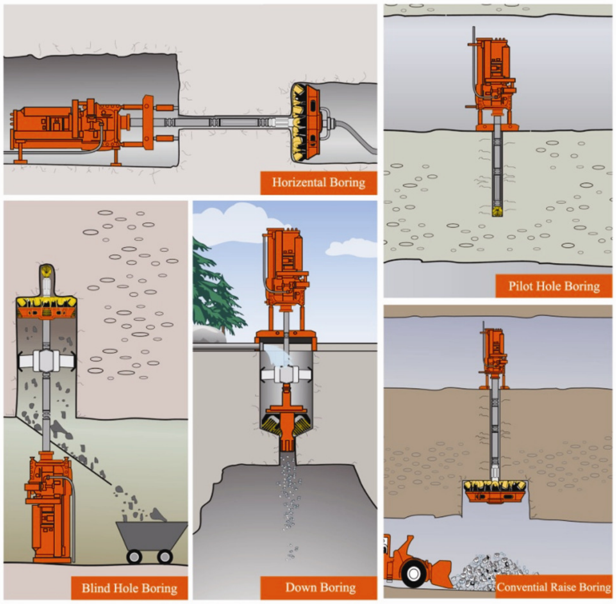

Fig. 1. Various types of RBM operations (Terratech Copmany's Brochure 2011)

The Shaft Boring Machine (SBM) is a development for the mechanized excavation of deep vertical blind shafts in hard rock conditions which can be used to sink deep vertical shafts with a diameter of up to 8.5 m (Ozdemir 1986). An overview of the system is shown in Fig. 2.

Fig. 2. An overview of SBM (Herrenknecht Copmany's Brochure 2011)

Table 1. Advantages and disadvantages of shaft sinking methods

<table>
<tr><th>Method</th><th>Usage</th><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>Drilling and Blasting</td><td>Applicable for all sinking operations</td><td rowspan="2">– Applicable in small shafts
– Low capital cost
– No need to mechanization
– Applicable in all sizes and angles</td><td rowspan="2">– Low performance rate
– Unsafe operation environment
– Ventilation system is required</td></tr>
<tr><td>Alimak method</td><td>Excavations in excess of 200 m in length, with no restriction on raise angles and sizes</td></tr>
<tr><td>Raise Boring Machine</td><td>Sinking shafts up to 1260 m in length and ranging from 0.7 m in diameter to 7.1 m</td><td rowspan="2">– Mechanized method
– High speed excavation
– Applicable in various types of boring operations
– Very safe as few people involved
– No in-hole ventilation system required
– Accurate drilling to accuracies of 0.035% deviation
– No blasting and thus no blasting related fractures
– Cost effective, especially where time is of the essence
– The drilling of long holes has now become the norm</td><td rowspan="2">– Straight line drilling makes it a relatively inflexible method
– Expensive on cost per meter
– Limited to certain sizes and lengths
– Fast drilling requires high tonnage chip removal
– Requires reasonably stable ground conditions</td></tr>
<tr><td>Shaft Boring Machine</td><td>Boring deep vertical shafts with a diameter of up to 8.5 m</td></tr>
</table>

The Alimak has been around since 1948. The Alimak Method consists of five steps which make up a cycle: drilling, loading, blasting, ventilation and scaling. It is better if the rock structure is continuous over several hundred feet vertically. The Alimak is by no means a new technology (Hustrulid 1982). It is a relatively fast method and can be used in excavations in excess of 200 m in length. Experience has shown that raises from 75 m to 150 m length are the most economical. A further advantage is that support components can be installed as one develops. The Alimak method offers solutions in the development of reef raises, boxholes, ventilation passes, shafts, etc. at practical diameters ranging from ±1.8 m to 6 m (Ferreira 2005). Drilling and blasting is a conventional method with no mechanization in which the operations handled by manpower (Hustrulid 1982). Table 1 shows advantages and disadvantages of these methods.

3. Decision making

Decision making is the study of identifying and alternatives based on the values and preferences of the decision maker. Making a decision implies that there are alternative choices to be considered, and in such a case we want not only to identify as many of these alternatives as possible but to choose the one that best fits with our goals, objectives, desires, values, and so on (Harris 1998). Decision making process can be divided into eight following steps (Fülöp 2005):

- Define the problem.
- Determine requirements.
- Establish goals.
- Identify alternatives.
- Define criteria.
- Select a decision making tool.
- Evaluate alternatives against criteria.
- Validate solutions against problem statement.

Various tools can be used to select the best alternative, including expert systems, Delphi decision making process, paired comparison, grid analysis, influence diagram, pro/con approach, decision tree, game theory, cost/benefit analysis, multi-voting technique, linear programming, trial and error approach, affinity diagrams and multiple criteria decision analysis.

Expert systems try to make decisions base on some rules and the knowledge of experts (Kreider *et al.* 1992). This method is based on personal judgment and provides no guarantee about the quality of the rules on which it operates. Moreover, these systems are not optimal for all problems, and significant knowledge is needed to obtain accurate consequences (Denby, Schofield 1990).

The Delphi decision making process was developed in the early 1950s. In this method, a series of surveys, questionnaires, etc. are sent to selected respondents who are selected because they are experts or they have significant knowledge (the Delphi group). The group does not converse in person (Yang, Hsieh 2009). All exchange of information or idea is normally in letters. The responses are collected and evaluated to determine conflicting opinions on each point. The process goes on in order to work towards synthesis and building consensus. In this method, the success depends upon the respondents' proficiency and communication skill. Also, each response requires enough time for reflection and analysis (Clayton 1997).

Paired comparison analysis helps the user to evaluate the importance of a number of alternatives relative to each other. It is particularly useful where decision maker do not have objective data to base this on (Katz *et al.* 2001).

Grid analysis is a useful technique to make a decision particularly where the decision maker has a number of alternatives to choose from, and several factors to take into consideration. Grid analysis is a great technique to use in almost any decision where there isn't a clear and obvious preferred alternative (Pike 2004).

Influence diagram is beneficial where impacts are graphically represented for a decision situation. Influence diagrams provide an alternative to decision trees which grow exponentially with more parameters (Cobb, Shenoy 2008).

Pro/Con and the similar or related techniques (such as pro/con/fix, T-chart, weighted pro/con, force field analysis and plus/minus/interesting,) are the age old method of considering the pros and cons of two alternatives. A key restriction of these methods is that only two alternatives are considered simultaneously (Ullman 2006).

Decision tree is useful to visualize multi-stage decision problems while dealing with uncertain outcomes. It can be beneficial in making decisions between investment opportunities or strategies with constrained resources (Choi, Lee 2010).

Game theory is useful for making complex strategic decision where it is beneficial to consider the likely response of outside participants (e.g. government, competitors or customers). This method can be regarded as an extension to influence diagrams. Game theory needs some simplifying assumptions to restrict a decision to a solvable game problem which is the most important limitation of this method (Tsoukiàs 2008).

Cost/benefit analysis is bounded to making decision about financial problems or can be considered as an extension for evaluation of financial criteria to other decision making methods (Almansa, Martínez-Paz 2011).

Multi-voting technique is beneficial for group decisions to select fairly between a large numbers of alternatives. It is much more useful to omit lower priority options before using a more precise method to finalize a decision on a smaller number of alternatives (Ou *et al.* 2005).

Linear Programming is commonly used for optimization of limited resources. This is a mathematical method in which the objectives and constraints are presented in form of linear equations (Huang *et al.* 2010).

Trial and error approach is another method for decision making. The main restrictions of this technique are that impacts for decision failure should be small and suitable reaction shoud be implicated after the failure to ensure that acceptable cause/effect relationships are recognized in the learning procedure. As an instance, heuristic techniques are trial and error decision making approaches which start with a model that is refined with ongoing experimentation (Whitehead, Ballard 1991).

Affinity diagrams and the similar or related methods (such as KJ method) address information overload by classifying a number of ideas and large amounts of data using this qpproach. Affinity diagram is generally used as part of a brainstorming exercise (Ho *et al.* 1999).

The decision making problems in which the number of the alternatives and criteria is finite and the alternatives are specified explicitly are named multi-attribute decision making (MADM) problems. Multiple criteria decision analysis and the same or related techniques (such as grid analysis, Kepner-Tregoe matrix) are techniques provide a good compromise between intuition and analysis by using a systematic framework that evaluates options against a defined set of success criteria (Chang, Wang 2009; Zavadskas, Turskis 2010; Ulubeyli, Kazaz 2009; Ginevičius, Podvezko 2009). Analytical Hierarchy Process (AHP) is an enhanced multiple criteria technique that uses paired comparison with additional mathematics to help address the subjectivity and intuition that is inherent in a human decision making technique (Kahraman 2008).

In some cases decision criteria are not rigid, where the boundary between a value and its inverse is gradual and there is an inexact boundary or class overlap. Boolean logic is in binary form in which an element is false or true, an object fit in a set or it doesn't (Goetcherian 1980). Fuzzy logic began with the 1965 proposal of fuzzy set theory by Zadeh and permits the concept of nuance. Based on this theory, a proposition may be anything from hardly to approximately true. A fuzzy set does not have strictly defined borders. The notion of a fuzzy set is beneficial to dealing with imprecision problems with uncertain criteria and conditions (Zadeh 1965). A brief review of fuzzy sets, Fuzzy AHP and Fuzzy TOPSIS are presented in appendix A, B and C, respectively.

4. Case study

4.1. Parvadeh mine

The coal region of Tabas is divided into three sections; Parvadeh, Nayband and Mezino areas. These areas are shown in Fig. 3.

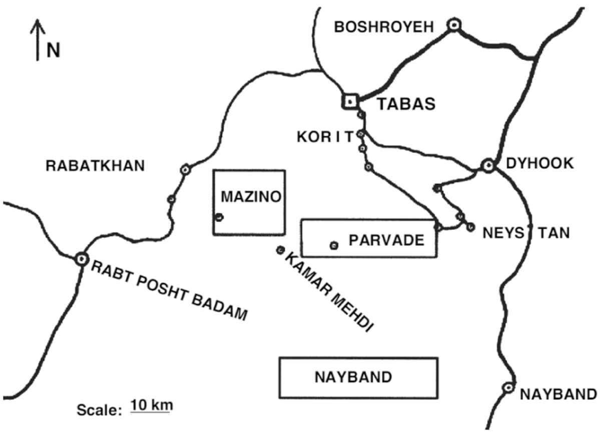

Fig. 3. Three areas in Tabas coal region (Asadi *et al.* 2005)

Parvadeh underground coal mine (Tabas coal mine No.1.) is a semi-mechanized coal mine, with a seam thickness of 1.8 m and dip angle of 29.5°, located in a remote rugged desert environment some 85 km south of Tabas city in mid east Iran, in an area of 1200 km^2, and production rate of this mine is about 4000 t of coal per day. Because of the suitable geometry of the coal seams and large extent of the deposit, mechanized longwall mining is applied. The face length (panel width) varies from 200 m to 220 m. The panel length is about 1000 m (Hosseini 2007). An international tender for Parvadeh coal mine was issued by the National Iranian Steel Company and a joint venture between IRITEC and IRASCO

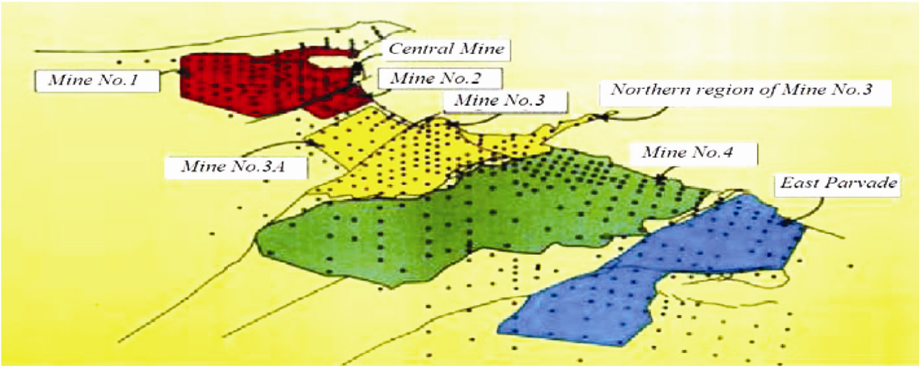

Fig. 4. Districts of the coal region of Tabas and location of exploration shafts (IRITECH 1992)

was selected as the preferred bidder. This project consists of preparation of infrastructures, carrying out engineering of one of the mine and supply of suitable technology and machineries for the development of the mine as well as training, technical assistance and commissioning of the longwall, coal handling and the coal preparation plants. Fig. 4 shows Parvadeh mine and other districts of the coal region of Tabas with location of the exploration shafts (IRITECH 1992; NISCOIR 1996).

4.2. Results

In this paper, FAHP is used to analyze the structure of the problem of shaft sinking method selection and to determine weights of the criteria, and FTOPSIS is used to obtain final ranking. The steps are summarized as follows:

Step 1. Forming a board of 13 academic and industrial experts are involved in mining and construction and explain the shaft sinking method selection problem.

Step 2. Decomposing the problem into a hierarchical structure in which the overall goal, at the top level of the hierarchy, can be separated into several criteria at a lower level of the hierarchy. The bottom level of the hierarchy represents potential alternatives. The aim of the hierarchy is to determine the importance rating of different methods based on the criterion that decision maker would like to attain in implication of the project, including water inflow rate (C_1), mechanization and advance rate (C_2), rock properties (C_3), hoisting depth (C_4), shaft diameter (C_5), safety (C_6), operating cost (C_7) and capital cost (C_8) and potential sub-criterions. Water inflow rate, capital and operating costs have negative impact on the selection and the rest of criteria have positive impact.

This purpose is done through pairwise comparison of the importance of different shaft sinking methods towards each criterion and pairwise comparison of the importance of different criteria towards the target.

Step 3. Developing a questionnaire to gather the expert knowledge regarding the subject. The experts will be asked to compare each of the paired factors in the matrices through questionnaires, regarding the technical parameters of the project. In this case, shaft diameter and hoisting depth will be 5.5 m and 580 m, respectively. At the first level, they need to state decisions about the relative importance of each criterion in terms of how it contributes to attaining the overall goal. Then a preference for each potential alternative in terms of its contribution to each criterion must be made.

A nine-point scale is suggested to state preferences between alternatives as extremely preferred, very strongly, strongly, moderately or equally, with pairwise weights of 9, 7, 5, 3 or 1, respectively. The values between mentioned points are the intermediate values for the preference scale. For the inverse comparisons, reciprocal values can be used. The matrix of paired comparison is constructed, after each factor has been compared.

Step 4. calculating the fuzzy pair-wise comparison matrix as follows (Jaskowski *et al.* 2010):

$$\tilde{x}_{ij} = (l_{ij}, m_{ij}, u_{ij})\,; \tag{1}$$

$$l_{ij} = \min\{x_{ij}^{k}\}, m_{ij} = \frac{1}{k}\sum_{k=1}^{k} x_{ij}^{k}, u_{ij} = \max\{x_{ij}^{k}\}, \tag{2}$$

where $\tilde{x}_{ij}$ indicates the fuzzy importance weights of each criterion which are calculated by experts, k is the number of expert and x_{ij} is the crisp weight of each criterion (Table 2).

Table 2. Fuzzy pair-wise comparison matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
C_1	(1.00 1.00 1.00)	(0.50 1.07 2.00)	(0.14 0.26 1.25)	(0.33 0.76 1.67)	(0.25 0.36 1.25)	(0.40 0.70 2.00)	(0.20 0.29 1.25)	(0.14 0.38 1.33)
C_2	(0.50 0.93 2.00)	(1.00 1.00 1.00)	(0.20 0.31 1.33)	(0.33 0.73 2.00)	(0.25 0.43 2.00)	(0.33 0.60 2.50)	(0.25 0.31 1.33)	(0.20 0.27 1.67)
C_3	(0.80 3.87 7.00)	(0.75 3.21 5.00)	(1.00 1.00 1.00)	0.60(1.89 3.00)	(0.50 1.12 2.00)	(0.60 2.40 3.00)	(0.40 1.06 2.00)	(0.40 1.25 2.50)
C_4	(0.60 1.32 3.00)	(0.50 1.33 3.00)	(0.33 0.56 1.67)	1.00(1.00 1.00)	(0.40 0.81 1.67)	(0.40 1.60 2.50)	(0.25 0.38 1.67)	(0.25 0.48 1.25)
C_5	(0.80 2.77 4.00)	(0.50 2.33 4.00)	(0.50 0.89 2.00)	0.60(1.23 2.50)	(1.00 1.00 1.00)	(0.80 2.30 4.00)	(0.33 0.47 1.67)	(0.25 0.40 1.67)
C_6	(0.50 1.36 2.50)	(0.40 1.67 3.00)	(0.33 0.41 1.67)	0.40(0.61 2.50)	(0.25 0.43 1.25)	(1.00 1.00 1.00)	(0.20 0.42 1.33)	(0.25 0.37 1.25)
C_7	(0.80 3.47 5.00)	(0.75 3.21 4.00)	(0.50 0.94 2.50)	0.60(2.63 4.00)	(0.60 2.13 3.00)	(0.75 2.30 5.00)	(1.00 1.00 1.00)	(0.67 1.02 1.50)
C_8	(0.75 2.65 7.00)	(0.60 3.67 5.00)	(0.40 0.80 2.50)	0.80(2.09 4.00)	(0.60 2.52 4.00)	(0.80 2.70 4.00)	(0.67 0.98 1.49)	1.00(1.00 1.00)

Table 3. The comparison of fuzzy weights

V(S1>S2)=1	V(S2>S1)=0.997	V(S3>S1)=1	V(S4>S1)=1	V(S5>S1)=1	V(S6>S1)=1	V(S7>S1)=1	V(S8>S1)=1
V(S1>S3)=0.687	V(S2>S3)=0.72	V(S3>S2)=1	V(S4>S2)=1	V(S5>S2)=1	V(S6>S2)=1	V(S7>S2)=1	V(S8>S2)=1
V(S1>S4)=0.899	V(S2>S4)=0.91	V(S3>S4)=1	V(S4>S3)=0.81	V(S5>S3)=0.9	V(S6>S3)=0.771	V(S7>S3)=1	V(S8>S3)=1
V(S1>S5)=0.776	V(S2>S5)=0.801	V(S3>S5)=1	V(S4>S5)=0.893	V(S5>S4)=1	V(S6>S4)=0.965	V(S7>S4)=1	V(S8>S4)=1
V(S1>S6)=0.938	V(S2>S6)=0.945	V(S3>S6)=1	V(S4>S6)=1	V(S5>S6)=1	V(S6>S5)=0.855	V(S7>S5)=1	V(S8>S5)=1
V(S1>S7)=0.664	V(S2>S7)=0.698	V(S3>S7)=0.997	V(S4>S7)=0.786	V(S5>S7)=0.898	V(S6>S7)=0.748	V(S7>S6)=1	V(S8>S6)=1
V(S1>S8)=0.662	V(S2>S8)=0.696	V(S3>S8)=0.975	V(S4>S8)=0.785	V(S5>S8)=0.896	V(S6>S8)=0.746	V(S7>S8)=0.999	V(S8>S7)=1

Thereafter, obtained weights of all criteria are compared by Eq. (B–6) and are presented in Table 3.

Step 5. Priority weights are determined by using Eq. (B–8) and are presented in Table 4.

Table 4. Final weight obtained of FAHP

	Local Weight	Global Weight
V(S1>S2,S3,S4,S5,S6,S7,S8)=	0.662	0.0979
V(S2>S1,S3,S4,S5,S6,S7,S8)=	0.696	0.1030
V(S3>S2,S1,S4,S5,S6,S7,S8)=	0.975	0.1443
V(S4>S2,S3,S1,S5,S6,S7,S8)=	0.785	0.1161
V(S5>S2,S3,S4,S1,S6,S7,S8)=	0.896	0.1326
V(S6>S2,S3,S4,S5,S1,S7,S8)=	0.746	0.1104
V(S7>S2,S3,S4,S5,S6,S1,S8)=	0.999	0.1478
V(S8>S2,S3,S4,S5,S6,S7,S1)=	1.000	0.1480

Step 6. By comparing the alternatives under each of the criteria, a decision matrix based on the experts' opinion is established and the performance ratings of the alternatives are determined by Eq. (3) (Torfi *et al.* 2010):

$$\tilde{x}_{ij} = (\tilde{x}_{ij}^{\ 1} \otimes \tilde{x}_{ij}^{\ 2} \otimes ... \otimes \tilde{x}_{ij}^{\ k}); \qquad k = 13. \tag{3}$$

The membership functions of fuzzy numbers which is shown in Table A.1 are used to quantify the linguistic values. Table 5 shows fuzzy decision matrix.

Then normalized fuzzy decision matrix is determined by Eqs (4) and (5).

$$r_{ij} = \frac{x_{ij} - \min\{x_{ij}\}}{\left[\max\{x_{ij}\} - \min\{x_{ij}\}\right]}, \tag{4}$$

the larger, the better type

$$r_{ij} = \frac{\min\{x_{ij}\} - x_{ij}}{\left[\max\{x_{ij}\} - \min\{x_{ij}\}\right]}, \tag{5}$$

the smaller, the better type

Step 7. The weighted normalized decision matrix is established using the criteria weights calculated by FAHP in step 5 by Eq. (1). Table 6 shows weighted normalized fuzzy decision matrix.

Step 8. The distance of each alternative from D^+ and D^- can be currently determined using Eq. (C–7) and Eq. (C–8). At last, FTOPSIS solves the similarities to an ideal solution by Eq. (C–9). The results of the analyses are summarized in Table 7. According to CL_i values, the ranking of the alternatives in descending order are RBM, drilling and blasting, alimak and SBM. Fig. 5 presented a schematic view of the rank of alternatives.

It can be inferred from Table 6 that shaft diameter (C_4), hoisting depth (C_5) and capital cost (C_8) are the main reasons to select SMB as the worst alternative. From technical and economical point of view, shaft sinking by the SMB impose a great amount of capital to the

Table 5. Fuzzy decision matrix

	A₁			A₂			A₃			A₄		
C_1	(1.87	3.11	4.22)	(2.33	3.88	5.51)	(4.65	5.96	6.97)	(7.20	8.18	8.79)
C_2	(6.94	7.8	8.56)	(6.22	7.21	7.89)	(3.96	4.65	5.69)	(3.33	3.82	4.36)
C_3	(3.12	4.02	4.97)	(3.27	3.68	5.06)	(4.86	4.78	5.95)	(5.20	5.96	6.87)
C_4	(0.41	1.04	1.37)	(2.17	3.11	3.82)	(5.33	6.13	6.91)	(6.88	7.65	8.68)
C_5	(3.09	4.15	4.85)	(5.28	6.12	7.06)	(6.25	6.96	7.66)	(6.89	7.21	8.19)
C_6	(7.22	7.98	8.54)	(6.58	7.16	7.44)	(4.14	4.87	5.66)	(2.23	3.15	3.77)
C_7	(2.36	3.93	4.69)	(3.16	4.06	4.86)	(4.78	5.22	6.90)	(7.19	8.02	8.66)
C_8	(7.83	8.36	8.76)	(6.38	6.88	7.71)	(4.43	5.10	5.64)	(0.29	1.21	1.94)

Table 6. Weighed normalized fuzzy matrix

	A_1			A_2			A_3			A_4		
C_1	(0.065	0.081	0.098)	(0.047	0.070	0.092)	(0.026	0.040	0.059)	(0.000	0.009	0.023)
C_2	(0.067	0.083	0.098)	(0.054	0.072	0.085)	(0.012	0.025	0.044)	(0.000	0.009	0.019)
C_3	(0.000	0.348	0.072)	(0.006	0.022	0.075)	(0.067	0.064	0.109)	(0.081	0.110	0.145)
C_4	(0.000	0.009	0.014)	(0.025	0.038	0.048)	(0.069	0.081	0.092)	(0.091	0.102	0.012)
C_5	(0.000	0.028	0.046)	(0.057	0.079	0.104)	(0.083	0.101	0.119)	(0.099	0.108	0.133)
C_6	(0.088	0.010	0.111)	(0.765	0.087	0.092)	(0.034	0.047	0.060)	(0.000	0.016	0.027)
C_7	(0.094	0.112	0.149)	(0.090	0.109	0.130)	(0.042	0.081	0.092)	(0.000	0.015	0.035)
C_8	(0.000	0.007	0.016)	(0.018	0.033	0.042)	(0.055	0.064	0.076)	(0.120	0.138	0.149)

Table 7. Final ranking of alternatives

Alternative	Ranking	CL_i	d^-_i	d^+_i
SBM	4	0.0603	0.484	7.544
RBM	1	0.0671	0.538	7.484
Alimak	3	0.0659	0.528	7.487
Drilling- Blasting	2	0.0666	0.534	7.487

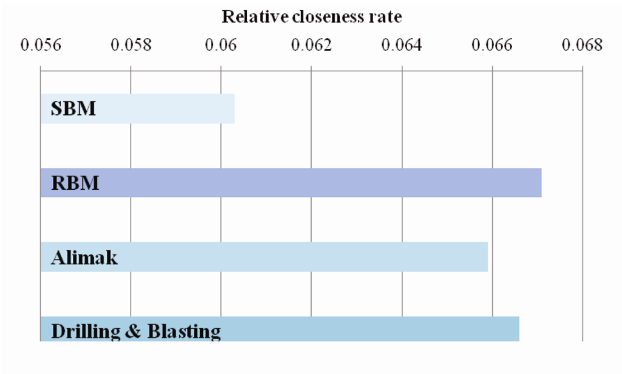

Fig. 5. The ranking of alternatives

project. Moreover, this method is appropriate for large diameter deep shafts. Therefore this method is appropriate for large scale shaft.

5. Conclusions

Shaft sinking is a critical part of underground construction operation and selection of an appropriate method to minimize sinking time and cost along with assure uninterrupted operation is of great importance. A number of techniques are available for shaft sinking operation. Each method has several inherent advantages and entails some limitations and problem. Consequently, selection of an appropriate method for shaft sinking operation requires consideration of many technical and economical criteria. In this study, a decision support system for shaft sinking method selection is presented to facilitate consideration of many effective parameters simultaneously in the shaft sinking method selection process. The present study explored the use of a hybrid method of Fuzzy Analytical Hierarchy Process (FAHP) and Fuzzy TOPSIS (FTOPSIS) in solving this multi criteria decision making issue. For this purpose, the existing criteria have been weighted by FAHP and then FTOPSIS is used to prioritize the alternatives. A real world case study of Parvadeh Coal Mine located in coal zone of Tabas in selecting the most appropriate shaft sinking method is presented to examine the practicality of the proposed model. This hybrid method considers both quantitative and qualitative effective parameters along with existing uncertainty, simultaneously and solves the problems of traditional shaft sinking method selection approaches. By applying the model, using of Raise Boring Machine (RBM) is selected as optimal method for shaft sinking in this mine.

Appendix A. Fuzzy sets

This theory can change concepts, variables and systems which are vague and imprecise to mathematical forms and this can provide background for reasoning, inference, control and decision making in uncertainty conditions (Ross 2004).

If $\tilde{A} = (a_1, a_2, a_3)$ is considered as a Triangular Fuzzy Number (TFN), where a_1, a_2, a_3 are crisp numbers and $a_1<a_2<a_3$, then membership function $f_{(\tilde{A})}$ is as Eq. (A–1):

$$\begin{cases} 0 & , \quad x < a_1 \\ (x-a_1)/(x_2-a_1) & , \quad a_1 < x < a_2 \\ (a_3-x)/(a_3-a_2) & , \quad a_2 < x < a_3 \\ 0 & , \quad x > a_3. \end{cases} \qquad \text{(A–1)}$$

A TFN is shown in Fig. A.1. The factors L, M and U represent the smallest possible value, the most promising and the largest possible value that describe a fuzzy event, respectively (Antuchevičienė 2005; Xu *et al.* 2010).

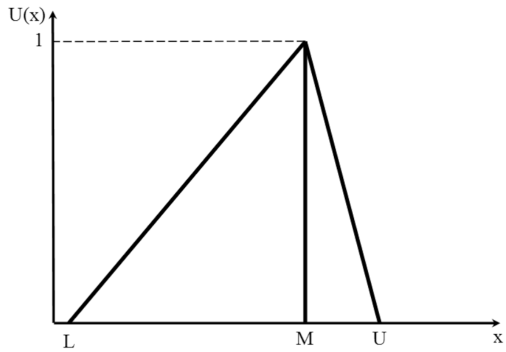

Fig. A.1. Triangular fuzzy number

If $\tilde{A}$, $\tilde{B}$ are two triangle fuzzy numbers as $\tilde{A} = (a_1, a_2, a_3)$, $\tilde{B} = (b_1, b_2, b_3)$ the mathematical relationship between $\tilde{A}$ and $\tilde{B}$ will be as follows:

$$\tilde{A}(\div)\tilde{B} = (a_1, a_2, a_3)(\div)(b_1, b_2, b_3) = \left(\frac{a_1}{b_1}, \frac{a_2}{b_2}, \frac{a_3}{b_3}\right); \qquad \text{(A–2)}$$

$$\tilde{A}(+)\tilde{B} = (a_1, a_2, a_3)(+)(b_1, b_2, b_3) = (a_1+b_1, a_2+b_2, a_3+b_3); \qquad \text{(A–3)}$$

$$\tilde{A}(-)\tilde{B} = (a_1, a_2, a_3)(-)(b_1, b_2, b_3) = (a_1+b_3, a_2-b_2, a_3+b_1); \qquad \text{(A–4)}$$

$$\tilde{A}(\times)\tilde{B} = (a_1, a_2, a_3)(\times)(b_1, b_2, b_3) = (a_1b_1, a_2b_2, a_3b_3); \qquad \text{(A–5)}$$

$$U = \{u_1, u_2, \ldots, u_m\}. \qquad \text{(A–6)}$$

A fuzzy set is characterized by a characteristics (membership) function, which allocates to each object a grade of membership belongs to [0–1] (Bardossy, Fodor 2004; Kala 2008). The characteristics function of fuzzy numbers, is applied to expert's questionnaire results to establish fuzzy weights, is defined in Table A.1. Fig. A.2. shows an interview of the membership function of fuzzy numbers.

Table A.1. Characteristic function of the fuzzy numbers

Linguistic terms	Corresponding Fuzzy Number
Very bad	(0, 0, 1)
Bad	(0, 1, 3)
Medium bad	(1, 3, 5)
Medium	(3, 5, 7)
Medium good	(5, 7, 9)
Good	(7, 9, 10)
Very good	(9, 10, 10)

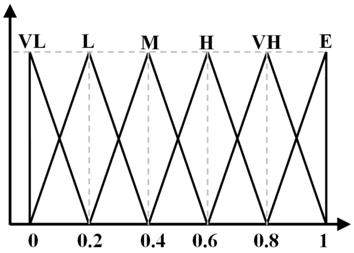

Fig. A.2. Membership function of the fuzzy numbers

Appendix B. Fuzzy AHP

Analytical hierarchy process (AHP) was introduced by Saaty (1980). This method is based on three fundamental concepts; structure of the model, comparative judgment of the options and the criteria and synthesis of the priorities. In order to develop a methodology for selection of the best alternatives in case of imprecision problems with uncertain criteria, AHP method has been combined with fuzzy theory by miscellaneous approaches (Buckley 1985; Chang 1996; Cheng 1997; Sivilevičius, Maskeliūnaitė 2010; Pan 2008). This method not only effectively handles the imprecision and uncertainty of the decision making but also supplies the flexibility and robustness required for the decision maker to realize the decision problem (Nang-Fei 2008).

Assume that $X=\{x_1, x_2 \ldots, x_n\}$ and $U=\{u_1, u_2 \ldots, u_m\}$ are object and goal sets, respectively. Based on the extent FAHP methodology which was introduced by Chang (Chang 1996) each object is considered and extent analysis for each goal, g_i, is applied, respectively. Therefore, m extent analysis values for each object can be given as follows:

$$M_{gi}^1, M_{gi}^2, \ldots, M_{gi}^m,\ i = 1,\ 2,\ \ldots,\ n. \quad \text{(B–1)}$$

In the above M_{gi}^j (j = 1, 2, ... , m) are TFNs.

The procedure of implication of Chang's FAHP methodology can be divided into three following steps:

Step. 1. Determination of the value of fuzzy synthetic extent: the following equation is applied to determine the value of fuzzy synthetic extent with respect to i^{th} object:

$$S_i = \sum_{j=1}^{m} M_{gi}^j \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^j\right]^{-1}. \quad \text{(B–2)}$$

Performing the fuzzy addition operation of m extent analysis values for a particular matrix, the term of $\sum_{j=i}^{m} M_{gi}^j$ will be determined as:

$$\sum_{j=1}^{m} M_{gi}^j = \left(\sum_{j=1}^{m} l_i, \sum_{j=1}^{m} m_i, \sum_{j=1}^{m} u_i\right). \quad \text{(B–3)}$$

Performing the fuzzy addition operation of M_{gi}^j (j = 1, 2, ... , m) values, the term of $\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^j\right]^{-1}$ will be obtained as:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^j = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i\right). \quad \text{(B–4)}$$

Thereafter, the inverse of the vector the above equation can be computed such that:

$$\left[\sum_{n=1}^{n}\sum_{j=1}^{m} M_{gi}^j\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right). \quad \text{(B–5)}$$

Step. 2. Determining the degree of possibility: the degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ can mathematically expressed by Eq. (B–6):

$$V(M_2 \geq M_1) = \sup_{y \geq x}\ [\min(\mu_{M1}(x), \mu_{M2}(y))]. \quad \text{(B–6)}$$

Assume that d is the ordinate of highest intersection point, D, between μ_{M1} and μ_{M2} (Fig. B.1).

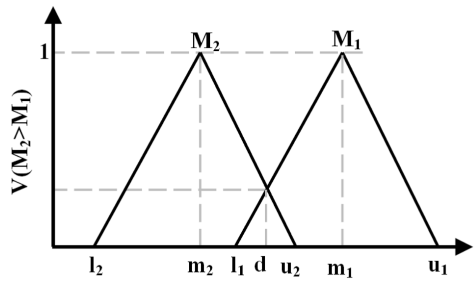

Fig. B.1. The intersection between *M1* and *M2*

Eq. (B–7) can be also defined as:

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M2}(d) = \begin{cases} 1 & \text{,if } m_2 \geq m_1 \\ 0 & \text{, if } l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & \text{, else} \end{cases} \quad \text{(B–7)}$$

The values of $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$ are needed to compare M_1 and M_2.

Step. 3. Determining the weight vector: Eq. (B–8) can be implicated to determine the degree of possibility for a convex fuzzy number to be greater than k convex fuzzy numbers $M_i\ (i = 1, 2, \ldots, k)$:

$$\begin{aligned} &V(M \geq M_1, M_2, \ldots, M_k) = \\ &V[(M \geq M_1) and (M \geq M_2) \ldots and (M \geq M_k)] \\ &= \min V(M \geq M_i),\ \ i = 1, 2 \ldots k. \end{aligned} \quad \text{(B–8)}$$

For $d'(A_i) = \min V(S_i, S_k)$, $k = 1,2...,n; k \neq i$ and $A_i\left(i = 1,2\dots,n\right)$ are n elements, the weight vector is defined as:

$$W' = (d'(A_1), d'(A_2), ..., d'(A_n))^T. \quad \text{(B–9)}$$

Step. 4. Normalizing the weight vectors: the normalized weight vectors can be defined as:

$$W = (d(A_1), d(A_2), ..., d(A_n))^T, \quad \text{(B–10)}$$

where W is a non-fuzzy number.

Appendix C. Fuzzy TOPSIS

Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) approach was introduced by Hwang and Yoon (Hwang, Yoon 1981). This method is based on the concept that the separation of the best alternative from the positive and negative ideal solution should have the shortest and the farthest, respectively which seems rational (Lin *et al.* 2008; Tupenaite *et al.* 2010; Zavadskas *et al.* 2010; Zavadskas, Antucheviciene 2006). TOPSIS is an easy-to-apply method and the computations involved are uncomplicated.

For the situation of incomplete information and non-obtainable information, TOPSIS technique has been combined with fuzzy theory which uses the fuzzy numbers to allocate the relative importance of the criteria instead of crisp numbers (Ning *et al.* 2011). The approach to extend the FTOPSIS method can be summarized as follows (Chen 2000; Braglia *et al*. 2003; Wang, Chang 2007):

Assume that $\tilde{x}_{ij}, \tilde{w}_j;\ i = 1,2\dots,m;\ \ j = 1,2\dots,n$ are linguistic triangular Fuzzy numbers which are defined as $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ and $\tilde{w}_j = (a_{j1}, b_{j2}, c_{j3})$. To express the fuzzy MCDM in the form of matrix, Eq. (C–1) and Eq. (C–2) can be developed:

$$\begin{array}{c} \\ A_1 \\ \vdots \\ A_m \end{array} \begin{array}{c} C_1 \ \ \cdots \ \ C_n \\ \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{pmatrix} \end{array}; \quad \text{(C–1)}$$

$$W = \left[\tilde{w}_1, \tilde{w}_2, ..., \tilde{w}_n\right]. \quad \text{(C–2)}$$

where $\tilde{x}_{ij}$ donates the performance rating of the i^{th} alternative (A_i) concerning the j^{th} criterion (C_j). Also the weight of C_j is represented by $\tilde{w}_j$.

The normalized Fuzzy decision matrix ($\tilde{R}$) and the weighted Fuzzy normalized decision matrix can be expressed as Eq. (C–3) and Eq. (C–4), respectively:

$$\tilde{R} = [\tilde{r}_{ij}]_{m \times n}. \quad \text{(C–3)}$$

$$\tilde{V} = \begin{bmatrix} \tilde{v}_{11} & \tilde{v}_{12} & \cdots & \tilde{v}_{1n} \\ \tilde{v}_{21} & \tilde{v}_{22} & \cdots & \tilde{v}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{v}_{m1} & \tilde{v}_{m2} & & \tilde{v}_{mn} \end{bmatrix} = \begin{bmatrix} w_1\tilde{r}_{11} & w_2\tilde{r}_{12} & \cdots & w_n\tilde{r}_{1n} \\ w_1\tilde{r}_{21} & w_2\tilde{r}_{22} & \cdots & w_n\tilde{r}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ w_1\tilde{r}_{m1} & w_2\tilde{r}_{m2} & & w_n\tilde{r}_{mn} \end{bmatrix}. \quad \text{(C–4)}$$

The procedure of implication of FTOPSIS can be divided into 6 different steps.

Step. 1. Choosing the linguistic ratings for alternatives: the linguistic ratings for alternatives $(\tilde{x}_{ij}; i = 1,2...,m; j = 1,2...,n)$ concerning criteria and the appropriate linguistic variables $(\tilde{w}_{ij}, j = 1,2,...,n)$ for the weights of the criteria are selected.

Step. 2. Developing the weighted normalized fuzzy decision matrix.

Step. 3. Determining the positive and negative ideal solutions: The positive (A^+) and negative (A^-) ideal solutions are calculated as Eqs (C–5) and (C–6), respectively:

$$A^+ = (\tilde{v}_1^+, \tilde{v}_2^+, \tilde{v}_3^+ ..., \tilde{v}_n^+) = \left\{\max_i \ v_{ij} \middle| (i = 1,2,...,n)\right\}; \quad \text{(C–5)}$$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \tilde{v}_3^- ..., \tilde{v}_n^-) = \left\{\min_i \ v_{ij} \middle| (i = 1,2,...,n)\right\}. \quad \text{(C–6)}$$

Step. 4. Measuring the separation of alternatives from the positive and negative ideals: the separation of each alternative from positive ideal (d_i^+) and from negative ideal (d_i^-) can be calculated as follows:

$$d_i^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^+) \ , i = 1,2,...,m; \quad \text{(C–7)}$$

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-) \ , i = 1,2,...,m. \quad \text{(C–8)}$$

Step. 5. Calculating the relative closeness of each alternative to the idea solution: the relative closeness of each alternative to the idea solution is determined according to Eq. (C–9):

$$CL_i^* = \frac{d_i^-}{d_i^- + d_i^+}. \quad \text{(C–9)}$$

Step. 6. Final ranking: the alternative with maximum value of relative closeness (CL_i^*) will be selected as the best option.

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KOMPLEKSINIO MODELIO NAUDOJIMAS GRĘŽINIŲ ĮRENGIMO METODUI PARINKTI

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Santrauka

Gręžiniai yra labai svarbūs giliose šachtose ir požeminėse konstrukcijose. Gręžiniai įrengiami keliais tradiciniais ir mechanizuotais metodais. Mechanizuotos žemės kasimo technologijos yra galima alternatyva, gerinanti projekto įgyvendinimą, tačiau tam reikia didžiulių kapitalo išlaidų. Pasirinkimui įtaką daro daug tarpusavyje nederančių rodiklių, tad sprendimą priimantis asmuo turi rasti balansą tarp jų. Todėl gręžinių įrengimo metodo parinkimas yra daugiakriterinių sprendimų priėmimo problema. Šiame straipsnyje naudojama analitinio hierarchinio proceso ir TOPSIS (artumo idealiajam taškui) metodo neraiškioje aplinkoje kombinacija tinkamam gręžinių įrengimo metodui parinkti. Modelio naudojimo atvejis iliustruojamas realiu pavyzdžiu, sprendžiant gręžinių įrengimo problemą Parvadeh anglių kasykloje. Rezultatai rodo, kad keliamasis gręžimo įrenginys parenkamas kaip tinkamiausias gręžiniams įrengti šioje kasykloje.

Reikšminiai žodžiai: gręžinių įrengimas, keliamasis gręžimo įrenginys, gręžimo įrenginys, MCDM, neraiškusis AHP, neraiškusis TOPSIS.

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