Application of multiple-criteria decision making analysis in mine development planning

Sanja Bajić, Branko Gluščević, Dragoljub Bajić

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FOREWORD

After the consultations with business entities in the field of mining and environmental protection, faculties and scientific institutes, an initiative for organizing a scientific meeting on mining and environmental protection was taken in 1996. The Faculty of Mining and Geology in Belgrade, CENTER FOR ENVIRONMENTAL ENGINEERING, have organized the First Yugoslav Conference with International participants held from 25th to 27th April 1996 in Belgrade, Serbia. 2nd International Symposium was held in Belgrade from 25th to 27th 1998. 3th Symposium was held in Vrdnik from 21st to 23rd May 2001, 4th International Symposium was held in Vrdnik from 23rd to 25th June 2003, 5th International Symposium was held in Vrdnik from 10 to 13 June 2015, 6th International Symposium was held in Vrdnik from 21st to 24th June 2017, and 7th International Symposium was held in Vrdnik from 25th to 28th September 2019.

Due to the large number of subjective and objective reasons organization of the symposium was discontinued in 2003. On the basis of the conclusions made at the 7th Symposium MEP 2019 and great interest of domestic and foreign scientific and professional public, the Faculty of Mining and Geology in Belgrade, in cooperation with co-organizers (National University of Science and Technology "MISIS", Moscow, Russia Berg Faculty TU Košice, Slovakia, University of Ljubljana, Faculty of Natural Sciences and Engineering, Slovenia, Goce Delčev University in Štip, N. Macedonia and University in Banja Luka, Faculty of Mining, Prijedor, Republic of Srpska, Bosnia & Herzegovina, Association of Mining and Geology Engineers), shall organize the 8th International Conference Mining and Environmental Protection – MEP 2021.

Considering the overall work of the conference from 1996 until today, we are proud to celebrate this year the 25 years of work and existence of the International Conference on Mining and Environmental Protection - MEP For all these years, about 700 scientific and professional papers in this field have been published in the Proceedings of the International MEP Conference, and about 1500 participants from the country and abroad have attended the conferences.

Unfortunately, the situation with the Covid 19 pandemic has changed a lot, including the number of participants who will be present at the Symposium. On the other hand, this year a large number of participants from the country and abroad are expected to attend the conference online.

The previous Symposium, were very successful and scientist and companies from many countries gathered to exchange information and research results. The objective of this Conference is to bring together engineers, scientists and managers working in mining industry, research organizations and government organizations, on development and application of best practice in mining industry in the respect of environment protection.

At the Book of Proceedings of 8th International Conference on Mining and Environmental Protection are 38 Papers. Almost half is from abroad, or their authors is from different countries. At least 100 authors and co-authors took part in the preparation of these papers. The papers were reviewed by Reviewers and Scientific Committee. Only high-quality papers were selected, from two side, one from the scientific basis and the second from point of view of applicability in resolving problems at the development of mining.

We are very grateful to the authors of the papers, who contributed to a great extent to the success of this meeting by having sent enough number of high quality papers, and thereby made the work of the reviewers a pleasant one in respect of selecting the best quality papers. Also, we would like to thank all of the participants in the Conference, as well as the sponsors who helped and enabled us to hold such a great meeting.

The Organizing Committee of the Conference made the decision to dedicate this Conference and this Proceedings to prof. dr Milivoje Vulić from the Faculty of Natural Sciences and Engineering, University of Ljubljana, longtime Vice President of the International Conference Mining and Environmental Protection, a great professor and scientist, a good man, who passed away between the last and this Symposium.

Editor

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C O N T E N T S:

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APPLICATION OF MULTIPLE-CRITERIA DECISION MAKING ANALYSIS IN MINE DEVELOPMENT PLANNING

Sanja Bajić, Branko Gluščević, Dragoljub Bajić

University of Belgrade, Faculty of Mining and Geology, Belgrade, SERBIA;
dragoljub.bajic@rgf.bg.ac.rs; branko.gluscevic@rgf.bg.ac.rs

Abstract: *The application of multiple - criteria analysis in decision making is particularly convenient in cases where sufficient information about the studied geological system is not available. As mines are characterized by dynamism in terms of continuous expansion from the beginning of ore exploitation to the very end of their working life, so the processes of excavating and draining the mine are very complex activities. The whole process requires continuous adjustment to the newly created conditions during the exploitation of ore, which conditions the establishment and development of an algorithm for a successful plan to excavate and protect mineral raw materials deposits from groundwater. Characteristics of the ore deposit itself are one of the most important factors in the judgement and decision-making of the optimal solution. Since mines are complex systems, choosing the right method of exploitation in complex geological conditions and drainage plans seems like a not-so-simple task. Fuzzy logic is useful for solving such complex and conflicting situations. Many real decision-making problems involve a factor of uncertainty, and most human assessments cannot always be accurately expressed. In addition, the criteria are often subjective and qualitative, as well as a large number of complex parameters, which negatively affect decision-making. It is precisely because of these conditions that fuzzy logic is proposed in multi-criterion decision-making because its application represents an effective way to present mathematically uncertain and inaccurate assessments, and because of the broad application when evaluating criteria and ranking alternatives. Developed complex interdisciplinary algorithm contributes to quality and sustainable management of mine development, both by choosing the method of excavation of deposits and protecting the mine from the influx of groundwater.*

Keywords: *underground exploitation, mining method, mine dewatering, fuzzy logic*

1. INTRODUCTION

The aim of this paper is to present the established and developed procedure method -algorithm applied when choosing the mining method for mining raw material deposit as well as when choosing the system for the protection from groundwatr and that in complex hydrogeologic conditions when there is underway a dynamic development of the mine that is subject to continual changes. This means application mode and solving the problems for the adequate choice of the variant in dewatering and mining method. Fuzzy logics – fuzzy optimization (method of fuzzy analytical hierarchical process – FAHP) is applied for explorations.

FAHP method is presented as a more advanced analytical method in relation to method AHP. It represents a combination of classical AHP method (Saaty, 1980) and the theory of set of triangular fuzzy numbers (Zadeh, 1965), and is implemented by using triangular fuzzy numbers (Chang, 1996, Deng, 1999). Modification of the method AHP into FHAP consists of the following relative relation of the importance of the optimization criteria is described by linguistic expressions defined by experts, and they are being modeled by fuzzy numbers, that is, fuzzy numbers describe elements of the matrix pairs that compare relative relationship importance of the optimality criteria.

In method FAHP comparing alternatives is done to form pairs that are being compared. The criteria for selection are being defined and are compared with sub criteria, and then for the same level depending on the importance of each, taking into consideration the calculation of the process that is made according to the defined hierarchical structure. When comparing fuzzy pairs, the decision maker examines two alternatives considering one criterium and points to the advantage, The results of the comparison, as numbers from FAHP scale (Tolga et al., 2005, Zhu et al.1999 Lamata 2004) are included into the adequate matrix on the basis of which are calculated local vectors of priority that is weight coefficient of compared elements As already mentioned, comparison of pairs is done by way of a comparing scale that adds numeric values.

Figure 1 shows the algorithm and steps that are being taken, beginning with defining specific problems when performing mines excavating and protection from groundwaters for the observed case until the selection of the optimal variant of the defense system. Knowledge, experience, subjective evaluations and intuition of experts have essential influence on all three parts of the algorithm.

The first part of the algorithm refers to designing variant solutions for protection of raw mineral deposits from groundwater, as well as the designing solutions for methods to perform excavating underground mines. The aim is to decrease groundwater levels under the level of the mining field, i.e. the drainage of the mine, and on the other hand determine the optimal mining method that would enable economically cost-effective exploitation of ore. In the second part, the analysis and discussion of the criteria that influence the decision when choosing the optimal way of drainage of mineral raw materials deposits and methods of mining excavation is conducted. In the second part, the analysis and discussion of the criteria that influence the decision when choosing the optimal way of drainage of mineral raw materials deposits and methods of mining excavation is conducted. The third part includes the MCDM model, i.e. the creation of a matrix of ratings of all criteria and sub criteria of each other and the matrix of assessments of all alternative solutions against all set criteria and sub criteria. After that, mathematical optimization calculations are performed, and a final decision is made.

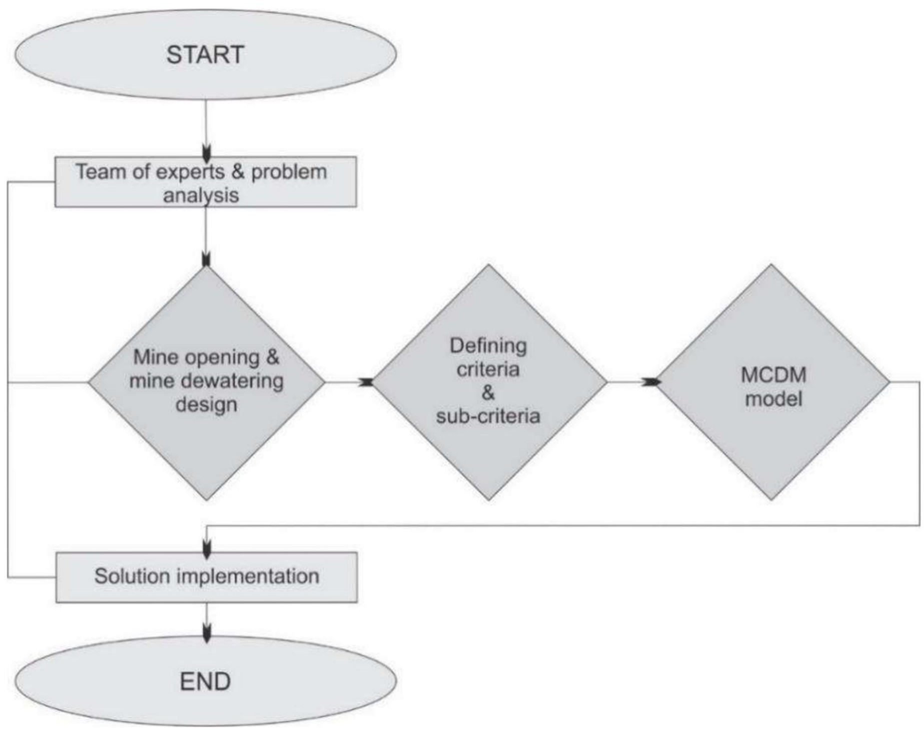

***Figure 1.** Algorithm of holistic approach for creating a sustainable plan for excavation and drainage of the Mine*

2. METHODOLOGY - ALGORITHM DISPLAY

Figure 2 shows a model for multicriteria decision making. A detailed description of all steps according to the multicriteria model (Figure 2) is presented below of this paper.

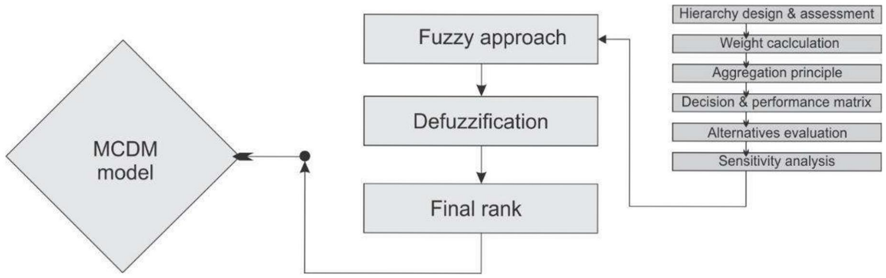

Figure 2. *Model for multi-criteria decision-making and selection of the optimal drainage solution and method of mine excavation*

At the beginning, the problem is discussed, the goal and the factors (criteria and sub-criteria) that influence the selection of the optimal alternative are discussed. Then a matrix of criteria and sub criteria is made against alternatives using the FAHP scale and triangular fuzzy numbers. First, hierarchical structuring of the problem is done. In the next phase, the evaluation and synthesis are performed, i.e., based on available information, the expert defines the relative relationship of importance of each pair of discussed elements in the matrix using the FAHP scale. Therefore, the expert answers the question of whether and how much one element is better than the other. First a matrix is made where criteria are evaluated relative to the goal, then a matrix where sub criteria evaluated, and then a matrix where alternatives are being evaluated:

The criterion evaluation matrices are defined as follows:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ a_{m1} & a_{m2} & \cdots & a_{mm} \end{bmatrix}$$

where: $a_{ij} = 1$ for every $i = j$, $(i, j = 1,2,...,m)$ and $a_{ij} = \dfrac{1}{a_{ji}}$.

Matrices for evaluating sub-criteria depending on the criteria:

$$A_j = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1k_j} \\ a_{21} & a_{22} & \cdots & a_{2k_j} \\ \cdots & \cdots & \cdots & \cdots \\ a_{k_j1} & a_{k_j2} & \cdots & a_{k_jk_j} \end{bmatrix}$$

where criterion Cj is composed of kj subcriteria,

Matrices for evaluating alternatives by comparing pairs of N alternatives in relative to each of the K sub-criteria:

$$Y_k = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1N} \\ a_{21} & a_{22} & \cdots & a_{2N} \\ \cdots & \cdots & \cdots & \cdots \\ a_{N1} & a_{N2} & \cdots & a_{NN} \end{bmatrix}$$

where $k = 1,2,...,K$, N- number of alternatives.

In the next step, the values of the vector of weight priorities are determined, using "fuzzy extent analysis ". According to the defined matrices from the previous step, the weight priorities values are defined using the fuzzy synthetic evaluation for the matrices for criteria.

$$w_i = \sum_{j=1}^{m} a_{ij} \otimes \left[\sum_{k=1}^{m} \sum_{l=1}^{m} a_{kl} \right]^{-1}$$

where $i = 1, 2, \ldots, m$

All obtained vectors of weight priorities - w_i are normalized using "extension principle", (Bajić et al., 2020). The final values of the weight of the sub-criteria are performed on the basis the aggregation principle: $w_j' = \left(\sum_{l=1}^{k_j} a_{il} \otimes \left[\sum_{i=1}^{k_j} \sum_{l=1}^{k_j} a_{il} \right]^{-1} \right) \otimes w_j$

where $j = 1, 2, \ldots, m$; $p = 1, 2, \ldots, k_j$

In matrixes, the alternative follows the step where again the so called „fuzzy extent analysis is performed, and evaluation of alternative performance $V_i\,(i = 1, 2, \ldots N)$ in reference to j sub criteria $(j = 1, 2, \ldots, K)$ is calculated as follows:

$$x_{ij} = \sum_{k=1}^{K} a_{ik} \otimes \left[\sum_{l=1}^{N} \sum_{m=1}^{N} a_{lm} \right]^{-1}$$

where $i = 1, 2, \ldots, N$; $j = 1, 2, \ldots, K$.

The next step is the application of the aggregation principle, to reduce two hierarchy tiers (criteria and sub criteria) to a single tier:

$$K = \sum_{j=1}^{m} k_j$$

k_j - number of sub-criteria in relation to the j-the criterion

The fuzzy decision matrix and fuzzy performance matrix are now calculated:

The fuzzy decision results from calculations of the "fuzzy extent analysis" from the previous step for the alternatives:

$$X = \begin{bmatrix} x_{11} & x_{12} & \ldots & x_{1K} \\ x_{21} & x_{22} & \ldots & x_{2K} \\ \ldots & \ldots & \ldots & \ldots \\ x_{N1} & x_{N2} & \ldots & x_{NK} \end{bmatrix}$$

Fuzzy performance matrix represents the overall performance of each alternative relative to all the subcriteria:

$$Z = \begin{bmatrix} x_{11} \otimes W_1 & x_{12} \otimes W_2 & \ldots & x_{1K} \otimes W_K \\ x_{21} \otimes W_1 & x_{22} \otimes W_2 & \ldots & x_{2K} \otimes W_K \\ \ldots & \ldots & \ldots & \ldots \\ x_{N1} \otimes W_1 & x_{N2} \otimes W_2 & \ldots & x_{NK} \otimes W_K \end{bmatrix}$$

By summing the elements from the rows of the fuzzy performance matrix, the ultimate values of the alternatives are calculated in the form of triangular fuzzy numbers:

$$F_i = \sum_{j=1}^{K} x_{ij} \otimes W_j$$

The final step includes defuzzification and ranking of alternatives The optimal alternative is the one with the greatest weight. The sum of the weights of all the alternatives is equal to zero. Here the weights of the alternatives are determined by introducing the optimization index λ:

$$I = \frac{\left(d\lambda + s + (1-\lambda)l\right)}{2}, \quad \lambda \in [0,1]$$

where: l, s and d are elements of the triangular fuzzy number.

3. RESULTS AND DISCUSSION

During exploitation, the mine is characterized by continuous expansion, by dimensions and by depth, and this requires an efficient and flexible system of dewatering. One of the key issues to be addressed during the technological process of exploiting mineral raw materials is the dewatering of deposits, and therefore the defense system must be designed to provide full protection of the mine from the influx of groundwater in order to continue the exploitation process in terms of enabling a smooth process of extraction of ore by applying one of the methods of excavation. The task of the system for dewatering in mineral raw materials deposits is to ensure the safety of operations, i.e. to ensure dry conditions of the lowest level of the mine.

Example 1. In order to display the developed algorithm and apply fuuzy multi-criteria optimization to solve problems related to mine drainage, one example was selected and presented, referring to the limonite mining deposit "Buvac" from the territory of Bosnia and Herzegovina (Bajic, 2016; Bajic et al., 2017; Bajic & Polomcic, 2019; Bajic & Polomcic, 2020). In the geological structure of the "Buvac" bearing are carbon-age rocks, represented by clastic rocks: slated alevrolites, claystone and sandstone; while carbonate rocks such as limestone, dolomites and ankerites occur to a lesser extent. Over the carbon deposits, there's a discordant pliocen-quartenary sediment. Lower and medium carbon belong to both siderit and limonite ore bodies. The significance of carbonated deposits is visible in that the primary deposits of iron ore are tied to them. Limonite ore bodies are created by oxidation processes of the upper parts of siderit ore bodies, and the most prepoctic product of oxidation processes is limonite. Also, in part, limonite occurs in the form of compact, microporororosity aggregates, along with gethite, lepidorokite and hematite. In addition to being the main component of limonite ore, getit also emerges as a standalone mineral within the ore mass, while limonite rarely appears as cement in mining breccia or even as an impregnation in clastic rocks.

The planned depth of the open pit matches the depth of the limonite deposit, which is about 170 m. Within the exploration area of the open pit "Buvac" the following types of aquifer have been taken into consideration: the aquifer in aluvial deposits and pliocene sands, the ore body aquifer, the karst-fractured aquifer in carbon rocks and waterless parts of the terrain. The problem of drainage of this open pit refers to the dewatering from the aluvial aquifer, i.e. the northern part of the open pit, and aquifer in the ore body (Figure 3). Common to all alternatives is an existing cut-off wall that stretches from the east to the south of the mine, as well as 8 wells that drain water from the ore body. Three drainage alternatives have been defined. The first alternative to the dewatering system consists of 33 wells on the north side of the open pit, with a total capacity of 107 l/s. The second alternative is a waterproof screen, on location instead of 33 wells from the first alternative, with a total length of 2km and a depth of 200m. The third alternative is 13 wells, a total capacity of 65 l/s and a waterproof screen 1km long and 200m deep.

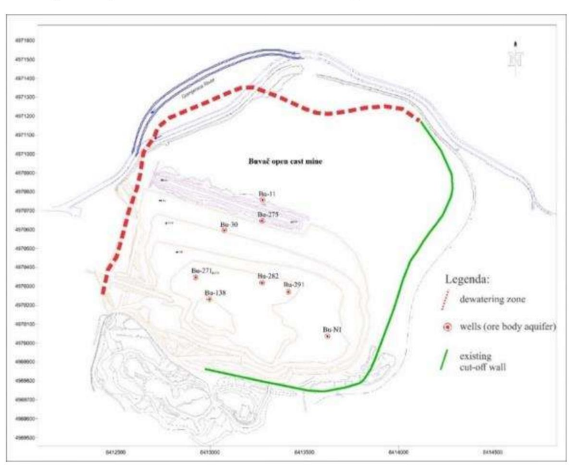

Figure 3. *Mine dewatering*

Related to the problem of drainage, factors that influence the selection of the optimal dewatering system have been analyzed in detail. These are technical criteria (time, adaptability to hydrological conditions, efficiency, flexibility and reliability), economic criteria (investment costs, system functioning costs and maintenance costs) and environmental impact criteria (declining groundwater levels, quality and quantity of exhausted water and energy savings). After mathematical optimization calculations were carried out in Fuzzy-GWCS (Bajic, 2016) the final values of all three alternatives in the form of a triangle fuzzy number were obtained, then the final value of the "weight" alternatives in the form of a non-fuzzy number and the value of the optimum index were shown in table 1. The best score is represented by the highest value of the "weight" alternative. In this way, the optimal variant of drainage is the alternative number two. In second place is alternative number 3, and as the most unfavorable solution is alternative 1.

Table 1. Ranking of alternatives applying the optimism index

	Fuzzy number			Optimism index			Final rank
	L	S	D	λ=0	λ=0,5	λ=1	
A1	0,066	0,309	1,684	0,321	0,277	0,270	3
A2	0,066	0,390	2,457	0,390	0,387	0,386	1
A3	0,037	0,301	2,233	0,289	0,336	0,344	2
The optimal alternative					A2		

Example 2. To solve problems related to the selection of methods of excavation of the underground mine, an example was selected and presented regarding the ore deposit "Borska reka" in Serbia (Bajic et al., 2020). The Borska River copper deposit is an integral part of the Timočka magma complex and is located in the far northwestern parts of Bor, under the Bor River Valley as part of the active mine "Jame". This ore deposit is the largest in Bor copper ore deposit and has been the subject of numerous analyses and studies for more than three decades. Just because it is located at great depth and the copper content in the ore is a very small selection of excavation methods, it seems like a very complex task. In geologic terms, the sediments are composed of volcanites and volcanoclastic rocks, quartz-diorite porphyritic rocks, hydrothermally altered volcanic and volcanoclastic rocks, pelites with tuffs and tuffites, conglomerates, sandstones, Quaternary alluvial sediments, and technogenic deposits. The mineral composition of the ore from Borska Reka includes chalcopyrite, covellite, chalcosine, rutile, hematite, magnetite, sphalerite, galenite, tetrahedrite, tennantite, digenite, cubanite, and native gold. The prevalent ore is pyrite, the dominant copper mineral is chalcopyrite, and there are covellite, chalcosine, and bornite to a lesser extent. On the other hand, enargite and molybdenite are very rare. Past exploration has revealed that the Borska Reka ore body is among very large deposits in the geometric sense, with elevated copper concentrations. Its maximum length is 1.410 m and maximum width 635 m, and the average is about 360 m. This ore body has an irregular shape and resembles a deformed flattened fallen cone with a base to the southeast and a top to the northwest. The bottom of the ore body consists of bor conglomerates. Numerous cracks and fissures are evident inside the ore body. They are mostly filled with alteration products and sulfide minerals.

In addition, five different alternatives (underground mining methods) were defined, including: Alternative 1—sublevel caving; Alternative 2—cut and fill; Alternative 3—shrinkage stoping; Alternative 4—block caving; Alternative 5—vertical crater retreat (VCR).

Related to the problem of choosing excavation methods, factors affecting the choice of optimal solution were thoroughly analyzed. These are criteria that are defined based on certain characteristics of the ore deposit and methods of underground excavation potentially selected. An operational model has been presented that includes a combination of technical (Depth of ore body, Thickness of ore body, Shape of ore body, Value of ore, Ore body slope (angle), Rock hardness and stability, Form of ore body and contact with neighboring rocks, Mineral and chemical composition of ore), production (Mining method productivity and output, Safety at work, Adverse environmental impact, Ore dilution, Ore impoverishment, Ventilation, Hydrologic conditions) and economic criteria (Capital expenditure, Mining costs, Maintenance costs). After performing mathematical optimization calculations in the Fuzzi-GVCS2 application (Bajić et al., 2020), the final values of all five alternatives in the form of a triangular fuzzy number were obtained, then the final values of the "weight" alternative in the form of a non-fuzzy number, as well as the values of the optimization index are shown in Table 2. The best result is represented by the highest value of the weight of the alternative. Based on the results, alternative 5 is the optimal underground mining method, followed in descending order by Alternative 2, Alternative 1, Alternative 3 and Alternative 4.

Table 2. Ranking of alternatives applying the optimism index

	Fuzzy number			Optimism index			Final
	L	S	D	α=0	α=0,5	α=1	rank
A1	0.02	0.196	1.955	0.1962	0.1975	0.1977	3
A2	0.023	0.222	2.019	0.222	0.2074	0.2059	2
A3	0.016	0.173	1.814	0.1724	0.1817	0.1826	4
A4	0.014	0.133	1.407	0.1339	0.1409	0.1416	5
A5	0.028	0.275	2.684	0.2752	0.2722	0.2719	1
	The optimal alternative			A5			

4. CONCLUSIONS

In order to obtain most efficient functioning of the process, various methods of multi-criteria optimization have been applied recently to simplify the decision-making. One of them is the FAHP method, which is suitable for understanding inaccurate and incomplete data, as well as for detecting relationships between the data.

The contribution of methods based on the fuzzy logic in science in decision-making consists of the ability to focus on overcoming deficiencies such as insufficient data availability. Since mines are complex geological systems, during exploitation they are characterized by constant dynamism in terms of the expansion of mines in space – both in dimensions in plan and by depth. Due to these facts, the whole process of mining activities requires continuous adjustment to the new conditions during the excavation and exploitation of ore. The contribution of methods based on fuzzy logic in decision-making science consists of the ability to focus on overcoming the uncertainties that arise when choosing methods for ore exploitation as well as when draining mines.

The interdisciplinary approach, which connects hydrogeology and mining to fuzzy optimization, i.e. mathematics, logic and multi-criteria decision-making, contributes to quality and sustainable management of drainage problems in areas and facilities threatened by groundwater, as well as solving the problem of mining, with the aim of making the best decision among several alternatives.

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