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# DEFINITION OF CRITERIA AND ALTERNATIVES FOR CHOOSING THE OPTIMAL MINING METHOD DEPOSITS WHEN APPLYING MULTI – CRITERIA OPTIMIZATION

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**Abstract:** When solving real problems, and to make a quality decision, it is necessary to consider a great number of often complex parameters. For these reasons, the development of decision-making process modeling has seen significant growth in recent years, and multi-criteria optimization models have stood out among them as useful for solving complex and conflicting phenomena. Multi-criteria optimization models make it easier for decision-makers to find the optimal solution in situations where there are many different criteria, which can often conflict with each other. The choice of the appropriate method of exploitation of mineral deposits follows the consideration of the problem and the approach to further development, which is primarily the determination of the criteria that influence the choice of the optimal alternative.

**Keywords:** multi-criteria decision-making; definition of criteria; underground exploitation

## 1 INTRODUCTION

The methods of underground exploitation include all technological stages of preparation and excavation of part of the block or the whole deposit. Excavation takes place according to a technological process that most often includes drilling, blasting, ore crushing, ventilation, loading and export of ore. In addition, backfilling or excavation operations may be required (depending on the excavation method). Depending on the shape of the deposit, its size, depositing conditions, physical and mechanical properties of the ore and accompanying rocks, hydrological conditions, sensitivity of the surface to mining operations, mineralogical and chemical composition of the ore, distribution of minerals and the value of the raw material will refer to which method of excavation will be used during exploitation of a c definite ore deposit. As a rule, ore bodies of irregular

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shape usually must be excavated by some method with backfilling. The size of the ore body is often a decisive factor, as it reflects the amount of ore reserves.

The most successful method will be the one that gives the highest production with the most useful components in the shortest time, with the lowest consumption of energy and materials, with complete safety for employees, and without unfavorable consequences for the further development of the mine. The methods used in underground exploitation are adapted to the rock conditions, shape, dimensions, strength and stability of the ore body. For successfully exploitation, infrastructure is needed for access to workplaces, production and transport of ore, ventilation, drainage, as well as equipment maintenance.

Choosing the most suitable excavation method in underground mining is not a simple process, because it requires working with a large amount of information about the characteristics of individual excavation methods, and very often there are several possible solutions for a specific application. Multi-criteria optimization methods have proven to be very useful for ranking alternatives, especially in cases when several complex criteria need to be considered at the same time.

Multi-criteria analysis represents a sub-discipline or branch of operational research, and essentially deals with the design of mathematical and computer models that serve as support for the evaluation of a final set of alternatives in the space of a set of criteria by one or more decision makers. Since this approach analyzes many often-conflicting criteria, its primary goal is to develop a methodology that will enable the aggregation of a set of criteria based on the subjective preferences of decision makers. Achieving the mentioned goal requires, most often, the application of complex procedures and methodologies.

Multicriteria analysis methods are designed to rank alternatives based on several selected criteria. They enable the comparison of both quantitative and qualitative criteria, and at the same time include in the analysis criteria that are expressed in different units of measure. Among the many methods of multi-criteria analysis that were developed to solve real problems, the following methods stood out: AHP (Analytic hierarchy process), TOPSIS (Technique for Order Performance by Similarity to Ideal Solution), PROMETHEE (Performance Ranking Organization Method for Enrichment Evaluations), ELECTRE (Elimination and Choice Expressing the REALITY) and VIKOR (Multicriteria Optimization and Compromise Solution), because they have proven to be useful tools when modeling problems in different fields of application.

## 2 DETERMINING THE CRITERIA THAT INFLUENCE THE CHOICE OF EXCAVATION METHOD

The problem related to the "Borska reka" copper deposit is to choose the appropriate method of mineral raw materials exploitation from deposits. In order to achieve the goal, it is necessary to consider the problem and approach further development, which is primarily to determine criteria and alternatives. Based on the researched literature related to the choice of methods in underground exploitation and the most significant factors that influence the choice of a suitable method, three criteria are distinguished: technical, production and economic (Ataei et al. 2008; Yazdani-Chamzini 2012).

The method of mining the deposit depends on its shape, size, depositing conditions, physical and mechanical properties of the ore and accompanying rocks, hydrological conditions, sensitivity of the surface to mining operations, mineralogical and chemical composition of the ore, distribution of minerals and the value of the raw material. Therefore, all these characteristics are extremely important and should be taken into account when making decisions about the optimal excavation method.

The method of excavation mining deposits depends on its shape, size, depositing conditions, physical and mechanical properties of the ore and accompanying rocks, hydrological conditions, sensitivity of the surface to mining operations, mineralogical and chemical composition of the ore, distribution of minerals and the value of the raw material. Therefore, all these characteristics are extremely important and should be taken into account when making decisions about the optimal excavation method.

In mining, we often encounter complex structured problems where the selection of the best from a group of possible alternative solutions is performed based on several criteria. The choice of criteria depends both on the natural conditions of the deposit and on techno-economic factors.

As a very specific ore deposit due to its location at a great depth and the copper content in the ore, which is low, it requires the consideration of many criteria. Criteria and sub-criteria that affect the choice of the optimal alternative are defined. Three criteria were singled out: technical, production and economic.

The given criteria are divided into sub-criteria, and in this case eighteen sub-criteria are defined, shown in table 1. Because these are different types of criteria, which are in opposition to each other, the application of multi-criteria decision-making (MCD) methods in the process of their prioritization is completely logical and justified.

In this paper, the criteria are defined based on certain characteristics of the ore deposit and underground excavation methods that are selected as potential. An operational model is presented that includes a combination of technical, production and economic criteria for choosing the optimal method of copper mining. An overview of criteria and sub-criteria is given in table 1 (Bajić, 2020).

**Table 1** Review of criteria and sub-criteria

| Criteria | Sign | Sub-criteria | Sign |
|---|---|---|---|
| Technical | T | Depth | $T_1$ |
| | | Thickness of ore body | $T_2$ |
| | | Shape of ore body | $T_3$ |
| | | Value of ore | $T_4$ |
| | | Slope angle | $T_5$ |
| | | Rock hardness and stability | $T_6$ |
| | | Ore body form and contact with adjacent rocks | $T_7$ |
| | | Mineral and chemical composition of ore | $T_8$ |
| Production | P | Productivity of the mining technology and production capacity | $P_1$ |
| | | Safety at work | $P_2$ |
| | | Environmental impact | $P_3$ |
| | | Ore dilution | $P_4$ |
| | | Ore impoverishment | $P_5$ |
| | | Ventilation | $P_6$ |
| | | Hydrology | $P_7$ |
| Economic | E | Capital expenditure | $E_1$ |
| | | Excavation costs | $E_2$ |
| | | Maintenance costs | $E_3$ |

**Technical criteria** represent one of three groups of criteria and include the geological conditions of the deposit, such as the depth and thickness of the ore deposit, the shape of the deposit or layers, as well as their extension and dip. The physical and mechanical characteristics of the ore and the surrounding rocks, as well as the mineralogical and chemical composition of the ore, also have an important role. **Deposit depth** - In many mines of underground exploitation of mineral deposits, the ore for exploitation is located at a depth of several meters or even 100 meters. For ore bodies that are hundreds or even thousands of meters below the surface, only some mining methods can be applied, considering their depth. (Javanshirgiv & Safari, 2017; Gluščević, 1974; Genčić, 1973; Đorđević, 2018; Torbica & Petrović, 1997). At greater depths, work with open excavations should be avoided and backfilling methods should be applied, and planned excavation should also be carried out. **Thickness of ore body** - Only certain excavation methods can be applied to narrower ore deposits, while all excavation methods can be applied to more powerful deposits. Deposits of small dimensions cannot be mined by highly mechanized technological processes, due to high investments in mining machinery and accompanying equipment and short exploitation time, which negatively affect the economy of production. **The shape of the deposit** - It is a very important parameter that should be considered, because it directly affects the choice of excavation method. Irregularly shaped ore bodies usually must be mined by some backfill method, and the size of the ore body is often a determining factor, as it reflects the amount of ore reserves (Javanshirgiv & Safari, 2017). **Value of ore** - If it is a valuable ore, a less effective method is often preferred, which gives a significantly higher utilization of the ore mass over an effective method with greater ore mass losses. If the ore has a high value, it is necessary to choose a method that will achieve as little losses as possible. If the ore is poor, the losses may be greater, but the impoverishment of the ore must be as little as possible. **Physical and mechanical characteristics of ore and surrounding rocks** - The strength of ore rocks represents the ability of the massif to resist crushing of ore for a certain period. It usually depends on the hardness of the rock. Physical and mechanical characteristics are of great importance for the choice of excavation method because the extent of excavation, the method of securing, the choice of appropriate equipment for drilling and ore loading, the dimensions of safety pillars, etc., depend on them. **Ore body form and contact with adjacent rocks** - Ore bodies with a clear contact and regular ore bodies enable the application of any method if the other conditions suitable for the mining method in question are met. If the supporting rocks contain a certain percentage of metal, sublevel caving mining method will be preferred. In the case of ore bodies that have an irregular shape and where the contact is not clear, the application of some methods, such as magazine or undercutting, is excluded, or difficulties are created during work and additional costs for preparation. For irregular ore bodies, methods with backfilling of empty spaces, or methods with roof demolition of barren rocks can be applied. **The mineralogical and chemical composition of the ore** is significant due to the presence of pyrite and pyrrhotite. In the case of ores that contain large amounts of pyrite and pyrrhotite, less preference is given to shrinkage stopping and sublevel caving mining method, and a relatively higher preference to one of the methods with backfilling. In addition to the mentioned difficulties, ores with a higher amount of pyrite and pyrrhotite, if they are exposed to air and moisture for a long time, oxidize, create difficulties in the flotation process and reduce the utilization of metal.

**Production criteria** represent important conditions that must be considered when evaluating and making a decision in choosing the optimal mining method for a selected ore deposit. When choosing an excavation mining method, the safety of employees must be taken into account, to ensure safety against fire in the pit, intrusion of underground and surface water, as well as to ensure good ventilation in the underground mine premises. Ensuring the appropriate production capacity in terms of volume and quality has a great impact on the price of the product, in this case - mined ore, as well as on the provision of the entire production plan. With low production costs, a greater economic effect of the mine is achieved. Lower production (excavation) costs are achieved if less material and manpower are used per unit of product (tons of mined ore). The workforce in underground mining exploitation is one of the most significant costs of production, which is why it is necessary to mechanize production processes as much as possible and to use mechanization to the greatest extent possible (Torbica & Petrović, 1997). **Productivity of the mining method and production capacity** - is expressed by the production intensity coefficient, which represents the ratio of ore production in one block during the year to per unit of excavation area. It can also be defined as the speed (required time) of excavation of individual excavation blocks or parts of the ore deposit. The productivity of the excavation mining method is of great importance in the economy of a mine, given that a higher productivity of the excavation method results in a higher production capacity. Excavation mining methods in which the entire ore surface or the ore surface on several horizons can be excavated at the same time can have a high general productivity or capacity, while the intensity of the applied method itself can be low. Conversely, if mining is done on only one part of the ore surface, or the entire surface, the method used may be very intensive, and the overall productivity or capacity of the mine may be low. However, high-productivity (mass) methods of high intensity are applied to large areas of the deposit, so the capacity of the mine is also large, even though excavation is performed only on one part of the ore surface. general productivity. Safety at work Safety at work is the main requirement for any excavation method, which must be met. The cost-effectiveness of operation must not allow the method to become dangerous to the life and work of people and call into question the safety of mine installations. When choosing a method of excavation, there must be safety that the application of a certain method will not cause fire, " break-in " of groundwater and surface water, destruction of above ground and underground walls of Mines and facilities in the mine and they will not endanger mining activities and miners. **Environmental impact** damage to the soil, which reduces the surface area and at the same time changes the quality and fertility of the soil, which occurs as a result of carrying out works in the underground exploitation of deposits of mineral resources, using certain excavation methods. This disrupts the natural whole. **Ore dilution** - represents a reduction in the content of useful components in the mass of mined ore compared to the content of useful components in the body of ore before mining.

**Ore impoverishment** during the exploitation of an ore deposit represents the ratio of the amount of tailings that got into the mine ore to the total amount of mine ore. Methods with the destruction of excavated spaces and shrinkage stopping method are characterized by greater impoverishment. Similarly, cutting and filling methods, in which ore is loaded by mechanical means directly from the backfill (scrapers or loading shovels), have greater impoverishment. Methods cutting and filling and block caving methods as a rule, have less impoverishment than other methods. **Ventilation** - It is necessary to provide good ventilation, i.e. supply of fresh air in sufficient quantities for normal operation and extraction of mine air, i.e. harmful gases and dust. Ventilation is the primary method of removing unsafe gases and dust from underground mining operations, such as drilling and blasting, from diesel equipment (carbon monoxide) or gases originating from rocks (e.g. radon gas). Hydrology In order to secure the surface from collapse and water penetration into the pit, it is necessary to apply methods with hydraulic-cement backfilling of empty spaces, or methods with leaving permanent safety pillars. These methods must also be applied when there are important objects above the ore deposit. If there are important objects on the surface above the ore deposit, such as a railway line, main road, aqueducts, etc., the application of sublevel caving methods is excluded. Sometimes it is more economical to move those objects, divert a railway or a road, and apply some highly productive methods than the cutting and filling method, which in that case would have to be applied.

**Economic criteria** include mining costs such as investment costs, excavation costs and maintenance costs. The assessment of these costs is necessary for the selection of underground mine excavation methods. Investment costs are defined as the amount of investment required before the mine starts to generate income. These are the costs of creating the opening rooms, the costs of excavation equipment as well as ventilation and drainage equipment. Investments in the purchase of mining machinery during the opening of an underground mine represent the largest investment expenditure.

Excavation costs include all costs: materials needed for preparation rooms, consumables, preparation and distribution of backfill paste in the pit, manpower for ore exploitation, drainage and ventilation.

Maintenance represents constant control over all means of work, as well as the performance of certain repairs and preventive actions, the goal of which is the constant, functional training and preservation of production equipment, plants and other machines and devices. Assets wear out over time and their working capacity decreases, as well as they are subject to breakdowns, breakages and damages, so interruptions in work occur. This causes the appearance of costs due to replacement and repair of parts, but also costs due to downtime in the production process (Jovančić, 2014). **Investment costs** are defined as the amount of investment required before the mine starts to generate income. This includes research, preparation, opening...Costs of construction of the opening premises, equipment for excavation and transport such as various machines, equipment for aeration (fan) and drainage. **Excavation costs** - materials for the construction of preparatory rooms, which include costs of consumables and energy for excavation, costs of making and distributing backfill pastes in the pit, costs of crushing, transport by belt conveyors and export of ore, labor costs for ore exploitation. With low production costs, a greater economic effect of the mine is achieved. Lower production (excavation) costs are achieved if less material and work force are used per unit of product (tons of ore mined). **Maintenance costs** include the maintenance costs of machines, equipment, existing buildings and plants, and installations, mine depreciation, mineral treasure maintenance costs, administrative overhead costs...

Considering all the previous facts and considering that the "Borska reka" copper deposit belongs to the group of ore bodies with a relatively high copper content, as well as due to the depth of the deposit at which it is located and the existence of objects on the surface of the terrain above the ore body, the paper justifies 5 applicable types methods, as possible for the excavation of such a deposit. For the exploitation of the "Borska Reka" deposit, highly capacitive and highly productive mining methods were considered, which would enable economically profitable mining of ore with a low metal content.

Five different alternatives have been defined in the form of five different methods of excavation in the underground exploitation of mineral deposits. Therefore, the system of methods of excavation of underground ore deposits is shown in table 2 (Bajić, 2020).

**Table 2** Proposal of alternatives as potential methods of excavation ore deposit

| | |
|---|---|
| Alternative 1 | Sublevel caving |
| Alternative 2 | Cutting and filling |
| Alternative 3 | Shrinkage stopping |
| Alternative 4 | Block caving |
| Alternative 5 | Vertical crater retreat (VCR) mining |

## 3 MULTI-CRITERIA OPTIMIZATION

If we start from the assumption that for the majority of decisions in concrete situations, the previously defined variant of the decision-making process can be valid when breaking down a decision into its parts, as well as that decisions need to be made on the basis of arguments, it can be stated that mathematical models and optimization methods have a significant, and in some cases an irreplaceable role in the most important stages of this process. The problem of managing a certain system is often indicated as unsolvable, however, with further study, it is often established that a solution exists, and even that there are several possible solutions. Then one encounters the problem of determining the "best" solution, i.e. optimization of that system.

The multi-criteria approach is a way to describe each specific problem as realistically as possible. The task of optimization is to choose the best variant, that is, the best solution from a number of possible ones, i.e. favorable variants for the adopted criteria. The best variant is the optimal solution of the optimization task and represents a compromise between the desire, i.e. criteria, and possibilities, i.e. restrictions. Optimization is performed using different methods, depending on the type of relations in the mathematical model, criterion function and limitations (Nikolić & Borović, 1996).

The word "optimum" is a synonym for maximum good or minimum bad (Opricović, 1992). To describe and achieve the best, optimization theory or decision theory is concerned. The decision-making process contains three general steps, namely: getting to know the system, determining the measure of effectiveness and optimization.

In addition to the fact that optimization theory is a numerical procedure for determining the optimum, it also deals with those problems that are not completely mathematically formulated.

Optimization models help in the decision-making process by enabling the expert to connect all the data and relationships in each situation, and the result should enable the choice of a good one, ie. optimal alternatives, while reducing all the complexities of the task. By applying optimization methods, the expert receives information that indicates the consequences and impacts of the chosen decision.

The application of the optimization method starts from a real problem that needs to be solved. Optimization models use the approach of "discrete models" when variant solutions are projected instead of creating a comprehensive mathematical model (Opricović, 1992).

When solving the multi-criteria decision-making problem, goals are defined, i.e. with which underground mining method to excavate the ore deposit, criteria are chosen to measure the achievement of goals, alternatives are specified, i.e. which methods come into consideration, the performance of alternatives is transformed according to different criteria so that they have the same metric, they are assigned weighting coefficients criteria in order to determine their relative importance, the appropriate multi-criteria decision-making method for ranking alternatives is chosen and finally the best alternative is determined, i.e. the optimal method for the appropriate area is chosen, i.e. a proposal for the final solution is given (Petković, 2016; Opricović, 1998) .

Figure 1 shows the levels (processes) at which multi-criteria optimization takes place.

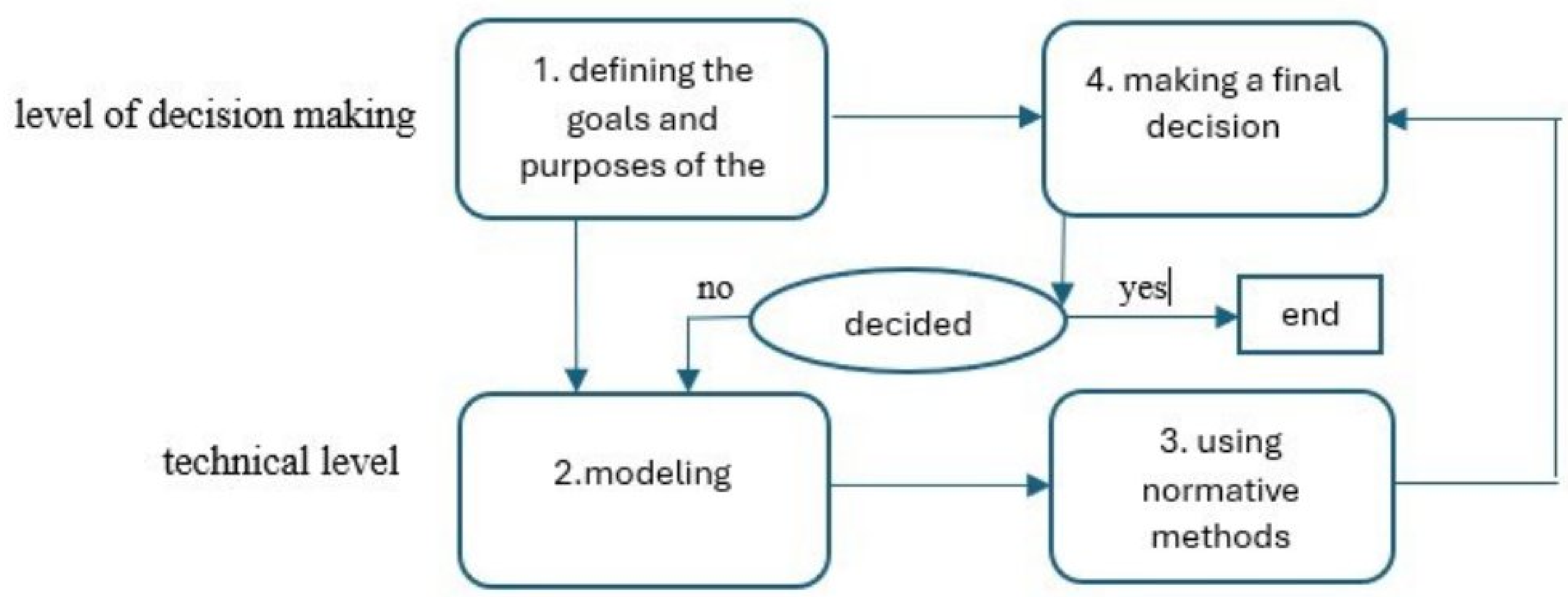


**Figure 1** Schematic representation of the optimization process

At the decision-making level, the main role is played by the "decision maker". The technical level suggests a set of good decisions (alternative solutions) to the decision maker, while make it easier the final decision. This implies that the proposed solutions should be clearly, briefly and precisely explained, as well as that their number should be relatively small. In the interactive process between these two levels, the proposed solutions are modified and generally the process converges on the final solution.

The procedure for solving multi-criteria decision-making tasks depends on the "intensity of conflict" of the criteria.

Defining the problem is the first and most important step in the selection of materials using multi-criteria decision-making (Rao, 2007). After the sets of criteria and alternatives are defined, a decision-making matrix is formed, which represents the basis for the evaluation of alternatives. The second step represents the definition of the preference regarding the importance of the selected criteria by the decision maker. These preferences are expressed through weight coefficients that range from 0 to 1, where a lower value of the weight coefficient means a lower relative importance of the criteria and conversely. It should be noted that the sum of all weighting coefficients of the criteria is equal to 1. When evaluating the weights of the criteria and deciding on the optimal solution, the values of the weighting factors are determined based on subjective opinion, by ranking information by priority and importance. With this approach, the decision-maker gives his opinion on the importance of the criteria for a given decision-making process in accordance with his system of preferences.

The third step is the selection of the solution method and the determination of the aggregate function in the material selection process using multi-criteria decision-making. The decision maker has at his disposal many methods for multi-criteria decision-making. Choosing a particular method is not a simple task and depends on the specific decision problem being solved and the goals set by the decision maker. The simpler the method, the better, however, complex decision problems may require the application of complex methods. The mathematical model, which is characteristic for each method, determines the aggregate function, the so-called decision rule that shows the overall assessment of the alternative, using data from the initial decision matrix, as well as the decision maker's preferences, expressed through the weight coefficients of the criteria. Based on these functions, it is possible to perform a complete ranking of the alternatives.

In the fourth step, the stability of the obtained solution, i.e. the ranking of alternatives, can be determined by the sensitivity analysis procedure. In this step, the decision maker can analyze whether a change in the value of the weighting coefficients of the criteria leads to a significant change in the ranks of the alternatives. If the decision maker is completely sure about the importance of the criteria, then this step can be omitted.

The last step is to choose the best alternative, ie. "optimal" alternatives. The choice is simple when some alternative, according to the aggregation function, dominates over the others. However, such situations are relatively rare, so in certain situations, two or more alternatives can be proposed as a solution to the multi-criteria decision-making problem. After choosing the final solution, the chosen solution is implemented, and the effects of its implementation are monitored and analyzed (Nikolić & Borović, 1996).

During the evaluation and optimization of excavation methods in the underground exploitation of mineral ore deposits, an example of the procedure for solving problems by applying multi-criteria decision-making using the FAHP method was given. The algorithm is shown in Figure 2.

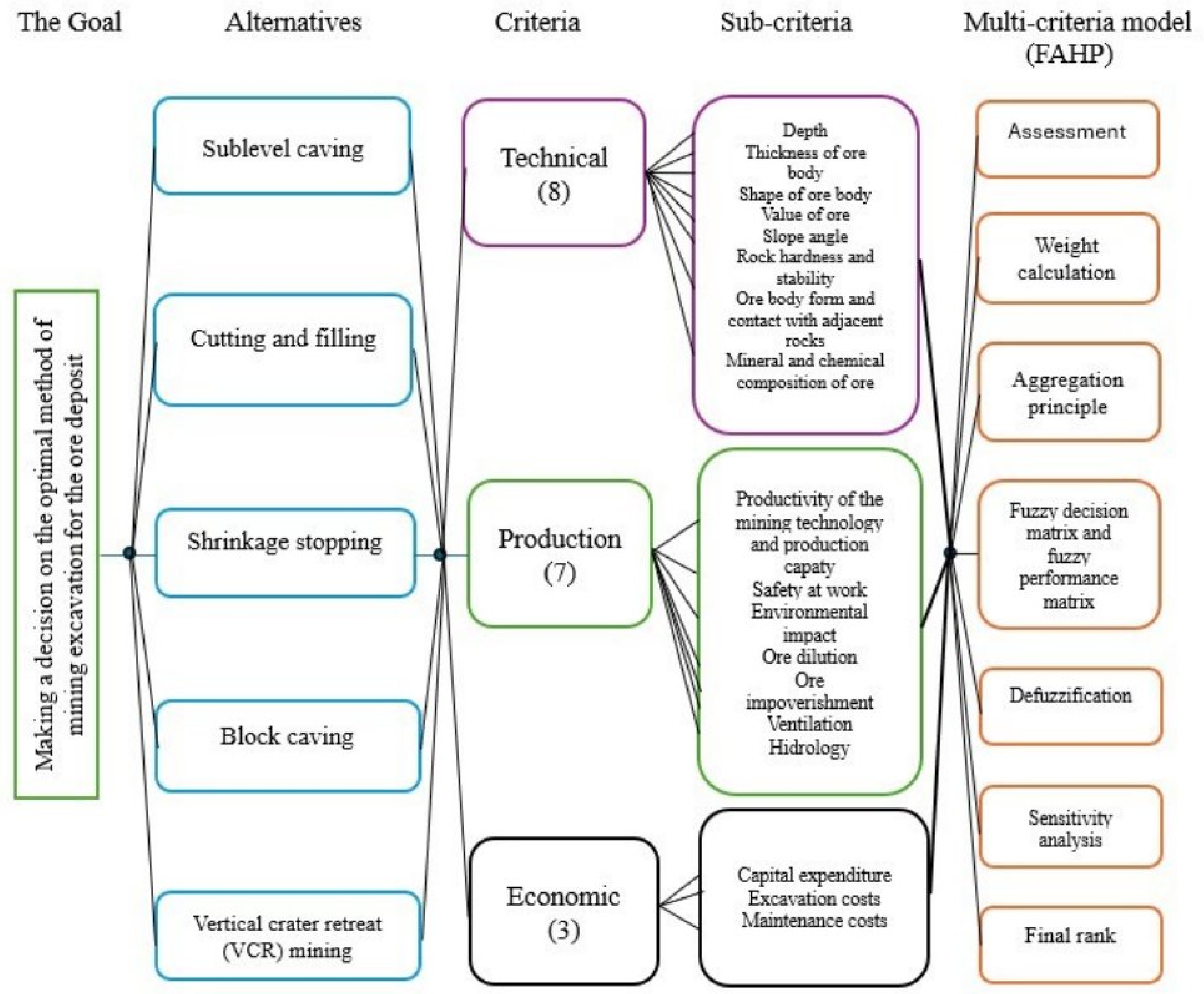


**Figure 2** Algorithm for multi-criteria decision-making when choosing the optimal excavation method using the FAHP method as an example

## 4 CONCLUSION

The methods of underground exploitation include all technological stages in the preparation and excavation of a specific ore deposit. Deciding on the optimal method of forging in underground mines represents a series of interconnected technological processes where the efficiency of the entire process depends on the efficiency of each of the processes individually. This means that many influencing factors should be considered, starting with the characteristics of the deposit. In addition to studying the characteristics of the deposits, it is necessary to take care of the safety of the workers during the exploitation of the mine, contribute to the low ore losses, ensure the necessary production capacity, as well as the low production costs. In this regard, it can be said that deciding related to the determination of the excavation method is not at all simple.

The "Borska reka" copper deposit represents the research area during the preparation of this paper. In this example, possible criteria and alternatives are defined in order to choose the optimal excavation method during the underground exploitation of mineral deposits.

Considering that the mining process of ore deposits can be carried out in various ways, many different methods could be applied. The possibility of ore extraction from the "Borska Reka" ore body was discussed with highly capacitive and highly productive mining methods. In a view of the ore body "Borska reka" belongs to ore bodies with a low copper content, as well as it is located at a certain depth of deposit, 5 applicable types of underground mining methods were studied: sublevel caving, cutting and filling, shrinkage stopping, block caving and vertical crater retreat (VCR) mining.

Various multicriteria optimization methods are used for efficiency and to simplify the decision- making process One of them is the FAHP method, suitable for understanding imprecise and incomplete data, as well as for discovering mutual relationships between these data.

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