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Application of Multi-Criteria Decision-Making Methods in Mineral Processing—A Review †

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Abstract: Multi-criteria decision-making (MCDM) methods represent an efficient mathematical tool for making selections between several alternatives which are seemingly similar and also when a large number of influential criteria need to be taken into consideration. In other words, MCDM methods make difficult choices easier, so that was the reason why they found applications in various areas of life, industry, science, etc. In mineral processing, when conducting scientific research or in industrial practice, it is often necessary to make different kinds of decisions based on several often-conflicting parameters such as technological, economic and environmental parameters. Making the wrong choices can affect the industrial process, result in additional expenses and endanger the health of workers and the environment, thus the application of MCDM methods can be the solution and give additional help in decision-making processes. In the past few decades, a large number of MCDM methods were developed, and some of them have found application in mineral processing for different purposes, such as the selection of various equipment (flotation machines, crushers, etc.), the selection of flotation collectors and other reagents used in mineral processing, and the selection of technologies for processing different raw materials, grinding circuits, and so on. In this paper, a comprehensive overview of the used MCDM methods and their applications regarding mineral preparation and processing will be given.

Keywords: MCDM; mineral processing; selection

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1. Introduction

Mineral processing represents a series of closely related technological processes (comminution, classification, concentration, dewatering, thickening, filtering, tailings disposal) in which the efficiency of the entire process depends on the efficiency of each individual process, or, it can be said that the entire chain is only as strong as the weakest link in it. This means that when managing some industrial processes, one should take into account a very large number of influencing factors, which in some cases can be a problem, especially if some of the parameters are outside of the set values, and it is not possible to control them in the right way.

It is noticeable that the problem of making strategic or operational management decisions in the preparation of mineral raw materials is not only complex but also very specific from the aspect of uncertainty, indeterminacy and the almost always present paucity and reliability of data. Based on the analysis of literary sources, it can be concluded that the problem has not been considered until the end or investigated in accordance with its importance.

In order to deal with this issue, support can be found in application of multiple- criteria decision-making (MCDM) methods, which represent an efficient mathematical tool for making selections between several alternatives which are seemingly similar and also when a large number of influential criteria need to be taken into consideration.

2. The Short History of MCDM

According to many authors, MCDM can be defined as a process of evaluating or ranking alternatives based on a set of mutually conflicting criteria [1–4].

Since the end of the last century, MCDM has been used for solving many decision-making problems, and as a result, numerous MCDM methods have been proposed, such as Simple Additive Weighting (SAW) by MacCrimon in 1968 [5], ELimination and Choice Expressing REality (ELECTRE) by Roy in 1968 [6], the Analytic Hierarchy Process (AHP) by Saaty in 1977 [7], the Technique for Ordering Preference by Similarity to Ideal Solution (TOPSIS) by Hwang and Yoon in 1981 [8], the Preference Ranking Organisation Method for Enrichment Evaluations (PROMEHTEE) by Brans in 1982 [9], the COmplex Proportional ASsessment (COPRAS) by Zavadskas et al. in 1994 [10] and VIsekriterijumska optimizacija i KOmpromisno Resenje (in Serbian), means Multicriteria Optimization and Compromise Solution (VIKOR) by Opricovic in 1998 [11].

In addition to the above MCDM methods, a significant emergence of newly proposed MCDM methods can also be observed, such as the Additive Ratio Assessment (ARAS) proposed by Zavadskas and Turskis in 2010 [12], the Multi-Objective Optimization by Ratio Analysis plus Full Multiplicative Form (MULTIMOORA) proposed by Brauers and Zavadskas in 2010 [13], the Weighted Aggregates Sum Product Assessment (WASPAS) proposed by Zavadskas et al. in 2012 [14], Evaluation Based on Distance from Average Solution (EDAS) proposed by Keshavarz Ghorabaee et al. in 2015 [15], the COmbined COmpromise SOlution (CoCoSo) proposed by Yazdani et al. in 2018 [16], and so on.

Many decision-making problems are related to the occurrence of inaccuracies, unreliability, or predictions. Therefore, the significant development and use of MCDM methods occurred after Zadeh proposed fuzzy set theory in 1965 [17]. Based on a fuzzy set theory, Bellman and Zadeh in 1970 proposed decision-making in a fuzzy environment and thus enabled the use of MCDM for solving more complex decision-making problems [18]. Certainly, the use of MCDM methods for solving decision-making problems in a fuzzy environment also required their adaptation for the use of fuzzy sets.

Significantly greater possibilities provided by fuzzy sets concerning the application of crisp numbers also influenced the proposal of new extensions of the fuzzy set theory, such as interval-valued fuzzy sets by Turksen in 1986 [19], intuitionistic fuzzy sets by Atanassov in 1986 [20], the neutrosophic set theory by Smarandache in 1998 [21], and so on.

The above-mentioned MCDM methods, as well as a considerable number of other MCDM methods and their extensions, have been applied so far for solving numerous decision-making problems in numerous areas, such as mining and mineral processing.

The procedure for solving decision-making problems using MCDM methods consists of several stages. Depending on the problem being solved, as well as its complexity, different authors have identified different stages in the process of solving the decision-making problem, but the following stages can be identified as common and significant:

- Identification of alternatives and selection of criteria for their evaluation;
- Criteria weights determination;
- Normalization;
- Aggregation;
- Ranking and selection.

There are several normalization procedures, and the following can be singled out as frequently used: the max normalization method, the max–min normalization method, the square-root normalization method and the logarithmic normalization method. Some MCDM methods can be used with any normalization method, such as the SAW method, while some methods prefer a certain type of normalization, such as the TOPSIS and VIKOR methods.

Different MCDM methods use different, especially for their proposed purpose, aggregations procedures or combine several aggregation procedures. Based on the approach used in aggregation procedures, MCDM methods can be classified into one of the following categories [22]:

- Pairwise Comparison Based Methods;
- Outranking Methods;
- Distance Based Methods;
- Other Methods.

The affiliation of certain previously mentioned MCDM methods to the mentioned categories is shown in Figure 1.

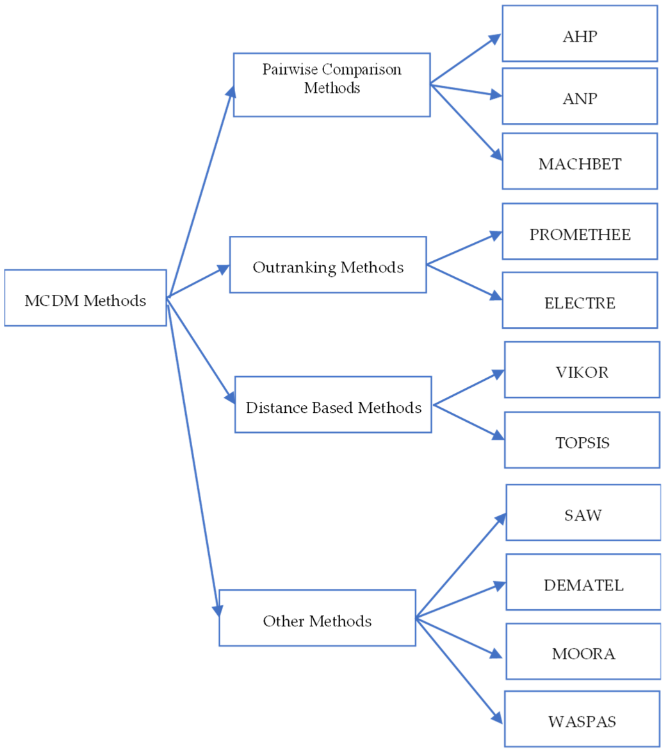

Figure 1. Classification of MCDM methods.

Until now, MCDM methods have been used for solving many decision-making problems, which are documented in many professional and scientific journals. Figures 2 and 3 shows the results of a search made in the WOS database using the keyword MCDM.

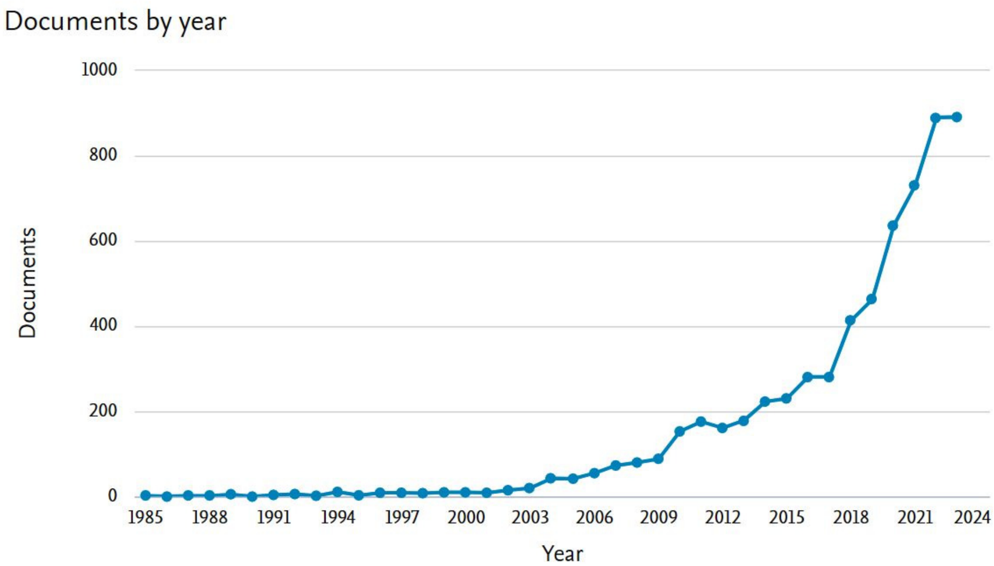

Figure 2. Number of published articles by year.

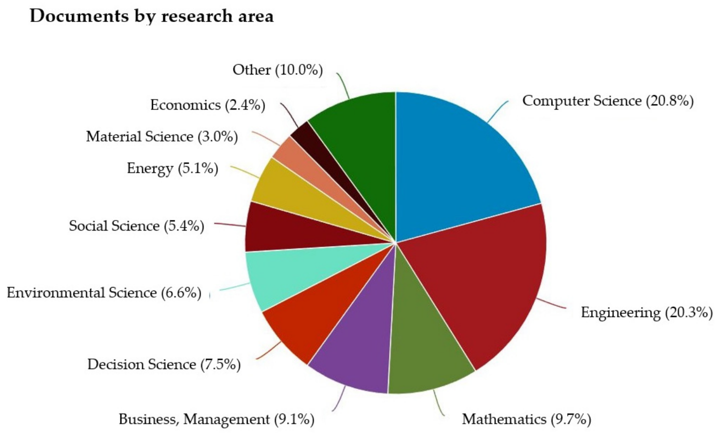

Figure 3. Documents by research area.

From Figure 2, it can be concluded that MCDM is an actual research area and that the number of published articles has an upwards trend, as well as that MCDM methods are used to significant extent for solving problems in engineering (Figure 3).

3. Application of MCDM in Mineral Processing

In mineral processing, when conducting scientific research or in industrial practice, it is often necessary to make different kinds of decisions based on several often-conflicting parameters such as technological, economic and environmental parameters. Making the wrong choices can affect the industrial process, cause additional expenses and endanger the health of workers and the environment, thus the application of MCDM methods can be the solution and give additional help in decision-making processes.

The application of MCDM methods for solving different problems in mineral processing has become more and more common over the years as researchers from all over the world recognized their benefits.

Safari et al. [23] used AHP for the selection of a mineral processing plant location using eight criteria. Bakhtavar and Lotfian [24] have also carried out the selection of a mineral processing plant location by applying fuzzy AHP and grey MCDM. They used six criteria for ranking six different locations. Štirbanovic et al. [25] applied Rough Set Theory (RST) for choosing the location for a flotation tailings dump. The evaluation of ten potential locations was carried out using nine criteria.

Kostovic and Gligoric [26] used the TOPSIS method for the selection of a collector in the flotation of lead–zinc sulfide ore, while Štirbanovic et al. [27] applied the VIKOR method for the selection of a collector in porphyry copper ore flotation. Kursunogluhe et al. [28] investigated the selection of an acid type for the recovery of zinc from a flotation tailing using the AHP.

Baral et al. [29] applied TOPSIS along with a line graph and spider diagrams for the optimization of leaching parameters for the extraction of rare earth metals. TOPSIS was also used by Kursuncu et al. [30] for the optimization of leaching parameters of copper from malachite ore.

Wang et al. [31] have performed multi-objective optimization of an industrial grinding and classification process by applying MABAC (Multi-Attribute Border Approximation area Comparison), along with TOPSIS and VIKOR methods. Weights of attributes were determined using AHP, EW (entropy weight) and GRA (grey relational analysis) methods.

The selection of a grinding circuit was performed using the MOORA method [32] and interval-valued intuitionistic fuzzy sets [33]. For the selection of a lead-zinc flotation circuit design, the WASPAS method with a single-valued neutrosophic set was applied [34], while the selection of a copper-pyrite flotation circuit design was carried out by applying the Preference Selection Index (PSI) method [35].

The selection of the most appropriate primary crusher for iron ore between gyratory, double toggle jaw, single toggle jaw, high speed roll crusher, low speed sizer, impactor, hammer mill and feeder breaker crushers, applying the AHP method, was the aim of the study performed by Rahimdel and Ataei [36]. Sitorus and Brito-Parada [37] used the results from the previous study and applied the Integrated Constrained Fuzzy Stochastic Analytic Hierarchy Process (IC-FSAHP) to test its applicability for this kind of decision-making problem. The selection of a rougher flotation machine for the processing of copper sulphide ore using TOPSIS and VIKOR methods was performed by Štirbanović et al. [38]. The selection of a grinding machine, drilling machine and milling machine was carried out by Son et al. [39] using two different MCDM methods, the FUCA method (Faire Un Choix Adéquat) and the CURLI method (Collaborative Unbiased Rank List Integration).

Some other applications of MCDM in areas related to mineral processing are the selection of a process for aluminium separation from waste cables using TOPSIS and WASPAS methods [40] and the selection of the best technology for acid mine drainage (AMD) treatment by applying five different MCDM methods: TOPSIS, VIKOR, MOOSRA, WASPAS and CoCoSo [41].

4. Conclusions

Since the introduction of the first multi-criteria decision-making (MCDM) methods in 1968, SAW and ELECTRE, a large number of new methods were developed and they have found applications in many areas of life, science, industry, etc. Mineral processing, in both the scientific and industrial sense, is very convenient for the application of MCDM methods because the functioning of the different processes is influenced by many, often conflicting, parameters which must be taken into consideration when making various decisions. Many researchers have recognized this, especially in the past few years, and applied different MCDM methods for a number of purposes such as the selection of locations of mineral processing plants and flotation tailing dumps; the selection of various equipment (flotation machines, crushers, etc.); the selection of flotation collectors and other reagents used in mineral processing; and the selection of technologies for processing different raw materials, grinding circuits, and so on. However, there are still many possible applications of MCDM methods in mineral processing that can and should be investigated.

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