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Entry

Multi-Criteria Decision Making (MCDM) Methods and Concepts

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Definition: Multi-criteria decision-making (MCDM) is one of the main decision-making problems which aims to determine the best alternative by considering more than one criterion in the selection process. MCDM has manifold tools and methods that can be applied in different fields from finance to engineering design. This entry aims to provide a survey on the MCDM concept, its applications, main categories, and different methods. The final section provides manifold information and statistics on the published works in the MCDM fields. Some of the main methods are also listed in this section.

Keywords: decision making; multi-criteria; survey; MCDM methods; MCDM concepts

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1. Introduction

There is no decision that can be addressed without referring to the decision-making process. Decision-making, as a mental complex process, is a problem-solving program that aims to determine a desirable result considering different aspects. This process can be rational or irrational, and on the other hand, it can use implicit or explicit assumptions that are influenced by several factors such as physiological, biological, cultural, social, etc. All these aspects together with authority and risk levels can affect the complexity level of a decision-making process. Nowadays, complex decision-making problems can be solved by utilizing mathematical equations, manifold statistics, mathematics, economic theories, and computer devices that help to calculate and estimate the solutions to decision-making problems automatically.

Multi-Criteria Decision Making (MCDM) or Multi-Criteria Decision Analysis (MCDA), is one of the most accurate methods of decision-making, and it can be known as a revolution in this field [1,2]. One of the first research studies on multi-criteria decision-making was developed by Benjamin Franklin when he published his research on the moral algebra concept. Several empirical and theoretical scientists have worked on MCDM methods to examine the mathematical modeling capability of these methods since the 1950s to provide a framework that can help to structure decision-making problems and generate preferences from alternatives. MCDM includes different methods that differ from each other in different aspects which will be discussed in the next sections [3].

This method considers different qualitative and quantitative criteria that need to be fixed to find the best solution. For example, cost or price and quality of the processes are among the most common criteria in many decision-making problems [4]. In addition, in these problems, expert groups provide different weights to the criteria that are based on the importance of each criterion in that specific case.

MCDM can be used for everyday problems in human lives. Still, when the problem is based on the more important subjects, for example in capital levels, the evaluation of criteria is an important issue. Therefore, in these situations, decision-making needs to be based on proper structuring and explicit evaluation of all the criteria using appropriate

software and tools. Practically, MCDM is used to deal with structuring, decision-making, and planning steps when the domain possesses manifold criteria to reach an optimum solution based on the deciders' preferences [4].

There are several types of MCDDM methods that are developed or improved by different authors during the last decades. The main differences between these methods are related to the complexity level of algorithms, the weighting methods for criteria, the way of representing preferences evaluation criteria, uncertain data possibility, and finally, data aggregation type [5].

In addition, all different types of MCDM possess specific and different merits and demerits that are expected to be explained specifically based on the methods. For example, Analytic Hierarchy Process (AHP) is easy to use and faces issues due to the interdependence between criteria and alternatives. On the other hand, in Fuzzy Set Theory (FST) using imprecise input is possible; however, this method is not easy to develop. In general, all MCDM methods have the advantage of considering decisions' disproportionate and contradictory impacts. On the negative side, the solutions that are generated by these methods are a compromise among several goals and this leads to not obtaining the optimal point due to the nature of the problem [3].

MCDM possesses manifold applications in different disciplines and areas ranging from economics and finance to engineering design and medicine. A recent article by Pramanik et al. [6] provided a comprehensive review of the application of different MCDM methods. A summary of their results is listed in Table 1.

Table 1. Applications of MCDM [6].

Application Fields	Examples of the Application Focus
Healthcare	The assessment of COVID-19 regional safety, occupational health, and safety risk assessment
Energy sector	Ranking renewable energy sources, techniques for energy policy
Engineering and Production	Engineering, material selection for optimal design, Optimum Process Parameters
Career and Job	Occupational stressors among firefighters, personnel selection problems, Job Choice
Supply chain management	Supporting sustainable supplier selection, green supplier evaluation, and selection
Organizations and corporates	System Selection Process in Enterprises, corporate sustainability
Education	Contextual Learner Modelling in Personalized and Ubiquitous Learning, E-learning
Transportation	Urban passenger transport systems, integrated transportation systems
Civil Engineering	Flood disaster risk analysis
Finance/economics	Project portfolio management

This entry seeks to give an overview of the MCDM idea, its applications, major categories, and methodologies for anyone interested in learning about and working in decision-making. After gaining an overview of the MCDM concept and its applications, the following sections are provided to discuss MCDM problems more specifically. For this, Section 2 will simply introduce the mathematical form of these methods, then different classifications of MCDM methods will be discussed in Section 3. Finally, the published articles on multi-criteria decision-making will be investigated, and some methods will be listed in the final section.

2. Solving an MCDM Problem—General Approach

Before introducing the format of these problems, the main concepts of MCDM are discussed in this section. MCDM includes different elements and concepts based on the nature of the decision-making problem. The main ones are as follows:

- Alternatives are "different possible courses of action"
- The attribute is defined as "a measurable characteristic of an alternative"

- Aggregation refers to "considering the performances of an alternative on the specific criteria for deciding on the alternative"
- Decision variables are defined as "components of alternatives' vector"
- Decision space is represented as "feasible alternatives"
- Measures are defined as "elements utilized to quantify an alternative to its attribute by assigning to the attribute numbers or symbols"
- Criteria are defined as "tools for evaluating and comparing alternatives from the viewpoint of the consequences of their selection"
- Preferences are defined as "how an alternative fulfills the need of a decision-maker regarding a given attribute"
- Decisions are different based on the type of problem that can include choice, ranking, and sorting problems [7,8]

There are different ways to interpret solving an MCDM problem. The process can be considered as choosing the best (most preferred) alternative from an alternative's set. It can be also explained as grouping alternatives (into manifold preference sets) and then opting for a small set from them. Furthermore, these problems aim to define the alternatives that are non-dominated or efficient. There is no way to move from a non-dominated solution to another solution without sacrificing at least one of the criteria that this point can help decision-makers to select a solution-set from the set of non-dominated ones [1]. In a mathematical form, an MCDM problem is defined as follows:

$$A = \{A_i \mid i = 1, 2, \ldots, m\}$$

where A is a distinct and finite set of alternatives, and m represents the number of them.

$$C = \{C_j \mid j = 1, 2, \ldots, n\}$$

where C is a set of certain criteria that are used to evaluate A, and n is the number of them. The alternatives are naturally homogeneous, but this point is not necessary for the criteria. That is to say, criteria can have different units without any inter-relationships, and with different conflicting objectives (minimizing objectives in some of them and maximizing in others).

$$W = \{w_j \mid j = 1, 2, \ldots, n\} \quad (1)$$

where W is a set of normalized weights assigning to each criterion based on their importance. The mathematical form of sets discussed above is a simple way to define an MCDM problem, and the gained information commonly is organized as a matrix form that is shown in Table 2.

Table 2. MCDM Matrix.

MCDM Matrix	C_1	C_2	...	C_n
A_1	x_{11}	x_{12}	...	x_{1n}
A_2	x_{21}	x_{22}	...	x_{2n}
...	...	...	x_{ij}	...
A_m	x_{m1}	x_{m2}	...	x_{mn}

In this matrix, x_{ij} represents the value of A_i related to C_j, and the matrix (M) and the weights' vector ($W = \{w_1, w_2, \ldots, w_n\}$) are the basic inputs for the MCDM problems. In fact, MCDM scores the alternatives and orders them based on the best to the worst. The main steps of all MCDM problems are shown in Figure 1 [6,9].

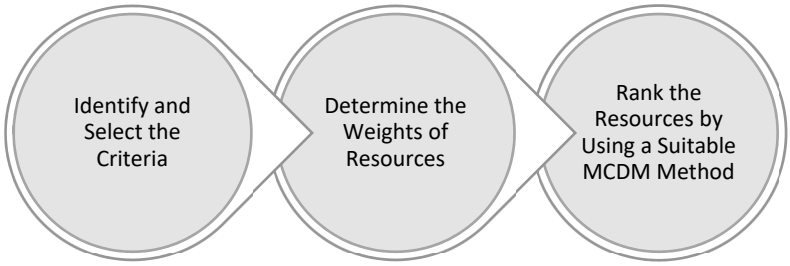

Figure 1. Steps of MCDM.

It should be noted that the columns and rows in the matrix can be changed based on the MCDM method used for more simplicity.

3. Multi-Criteria Decision-Making Categories

As discussed, there are manifold MCDM methods with different characteristics that can be related to many aspects from the quality of answers to the type of the problem these methods solve. Therefore, to gain a better understanding of the MCDM methodologies which helps to select an appropriate method for the problems faced, it is essential to identify the classification of MCDM problems. Different typologies and sub-groups considering different aspects of the problems are recognized in manifold studies. Here, some of the main sub-groups are listed, and then the most common classifying technique is explained in more detail.

Firstly, an important method considers the aggregation procedure type which is used to assess the criteria that can be considered to identify the MCDM classification. In this method which is mentioned by Zopounidis and Doumpos [10] the aggregation methods are as follows:

Outranking relations: When enough arguments are available to confirm that an alternative is as good as another one, using this method and its binary relations helps to assess the alternatives by evaluating their outranking degree.

Utility functions: The utility of an alternative is the performance of that alternative considering all of the criteria. This method is used to serve as an index that helps to decide during sorting the alternatives into the predefined sets.

Discriminant function: Although they are similar to the utility function, these models cannot be involved as a kind of preference model. These models do not work based on the preferences' orders among criteria domains and decision classes. In addition, it is a linear method with quantitative criteria (in nature or by quantifying the qualitative ones).

Function-free models: The form of these models is symbolic. That is to say, the overall performance of the alternatives is analyzed based on a specific decision rule.

Furthermore, the following categories are also used in the literature:

Compensatory, non-compensatory, and partial compensatory approaches: In addition to the above category type, MCDM can be categorized as compensatory approaches, non-compensatory approaches, and partial compensatory approaches. This approach is based on the negative criteria's feasibility on attributes when it is compensated by positive ones.

Individual or group decision-making: A simple approach is to distinguish between the MCDM methods based on whether it is an individual or a group decision-making which considers the number of decision-makers [11].

Qualitative/quantitative or certain/uncertain information: Information type that is qualitative/quantitative or certain/uncertain can be considered as another type of classification.

Tradeoff-based and non-tradeoff-based methods: Also, types of weighting methods that are generally two types tradeoff-based and non-tradeoff-based methods are another way to distinguish MCDM problems' types [8].

MODM or MADM: In one of the most commonly used methods, the criteria are considered as two types: (1) attributes and (2) objectives. Furthermore, Hwang and

Yoon [12] divided MCDM problems into two main categories based on the number of alternatives. Therefore, MCDM problems are categorized into two general sub-categories multi-attribute decision making (MADM) and multi-objective decision making (MODM). The sub-groups can be also named innumerable (with infinite admissible answers) and numerable (with finite admissible answers). In the following paragraphs, these sub-groups are defined in more detail.

MODM: MODM focuses on continuous decision spaces with an infinite number of alternatives and is also known as continuous problems of decision making. Here, a feasible region (where the alternatives lie) is considered as the solution to the decision-making problem. It is an optimization problem with no direct and specific alternative chosen as a solution. In these types, criteria are goals, and attributes are implicit. Although there is no clear goal and option, here the limitations are clear and decision-makers have a high level of interaction.

MADM: MADM is also known as discrete problems and concentrates on problems with explicitly known decision alternatives with finite numbers. It is an evaluation problem that chooses the solution between a discrete number of alternatives. In these types of MCDM, goals, attributes (that are criteria) and options are clear; however, the limitations are unclear and the interaction level between decision-makers is limited.

The different classification methods discussed above are summarized in Figure 2 [8,11,13].

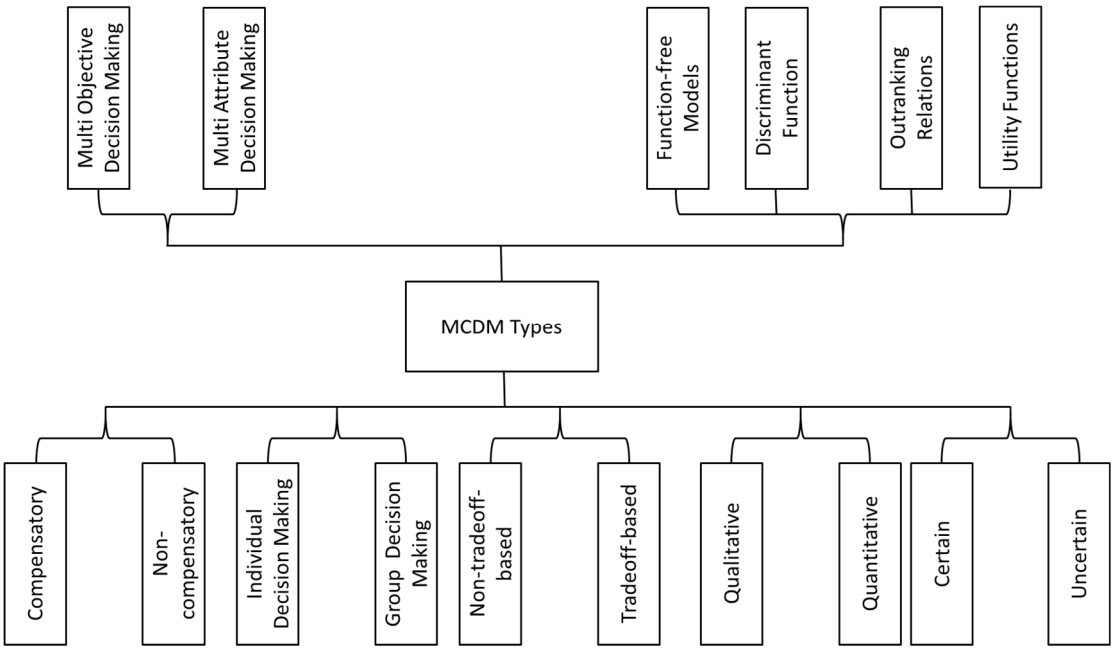

Figure 2. Different Classifications of MCDM.

4. Research on Multi-Criteria Decision Making

Several authors have focused on multi-criteria decision-making methods in their research studies. This section aims to investigate the number of articles in this area to evaluate the importance of MCDM methods in different subject fields and gain an overview of the most cited MCDM methods. Here, the results are obtained based on the "ScienceDirect" database (between 2012–2022) by using different keywords. Firstly, the results show that the number of articles focused on this field is 10,116, and 7619 based on using "multi-criteria decision making" and "MCDM" keywords, respectively (conducted on 25 April 2022). The percentages of the studies on MODM and MADM are shown in Figure 3 that is based on searching "MODM," multi-objective decision making," "MADM," and finally "multi-attribute decision making" keywords on the "ScienceDirect" database during the selected time period.

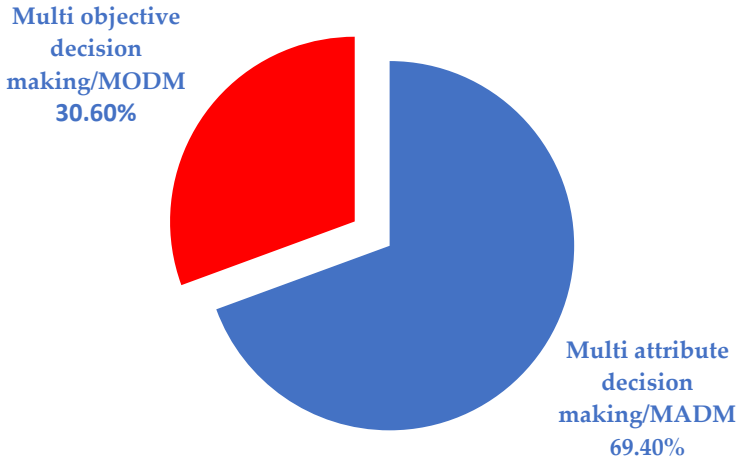

Figure 3. Percentages of Articles Focusing on MODM and MADM.

Furthermore, the number of articles in this field and by using "multi-criteria decision making" keywords are shown in Figure 4 helping to investigate the changes in the number of results in this method during the time period. Figure 4 clearly shows an increase in the results in the last years that can prove the popularity of MCDM methods in recent studies. Due to the multi-dimensionality of this crisis and the complexity of the socio-economic and health systems, MCDM approaches have grown in popularity for simulating COVID-19 concerns [14]. It should be noted that MCDM tactics are directly related to solutions to sustainability issues. This emphasises the significance of MCDM techniques and their rapid growth [15].

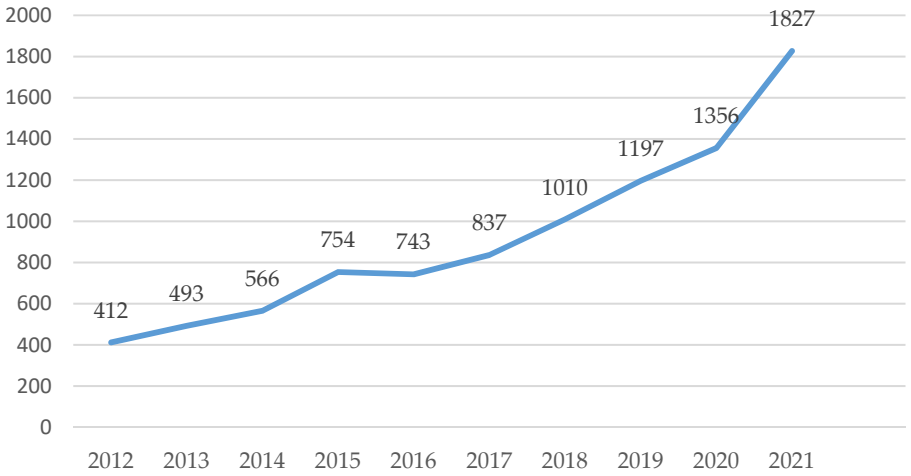

Figure 4. Studies on MCDM—Number of Articles from 2012 to 2021.

On the other hand, as discussed in the previous sections, MCDM methods are utilized in manifold fields from the energy to business area. For this, the number of results is also shown in Figure 5 based on the subject area of the studies (considering some articles have more than one subject area). The result shows that MCDM methods are used in a vast range of research fields such as mathematics, energy, computer science, etc.

The next part of this section is provided to investigate the prevalence of using different MCDM methods in different articles. For this purpose, firstly, a list including 60 different methods is provided that are taken from manifold literature reviews and research articles. The methods and number of results (based on the "ScienceDirect" database, and between 2012 and 2022 conducted on 21 April 2022) are listed in Table 3. It should be noted that generally the complete names were used in the search box; however, when the number of results was very limited, or the abbreviation form of the method is more popular (for

example for TOPSIS), abbreviation forms were also used, and the maximum number of results were chosen, and listed in the Table 3.

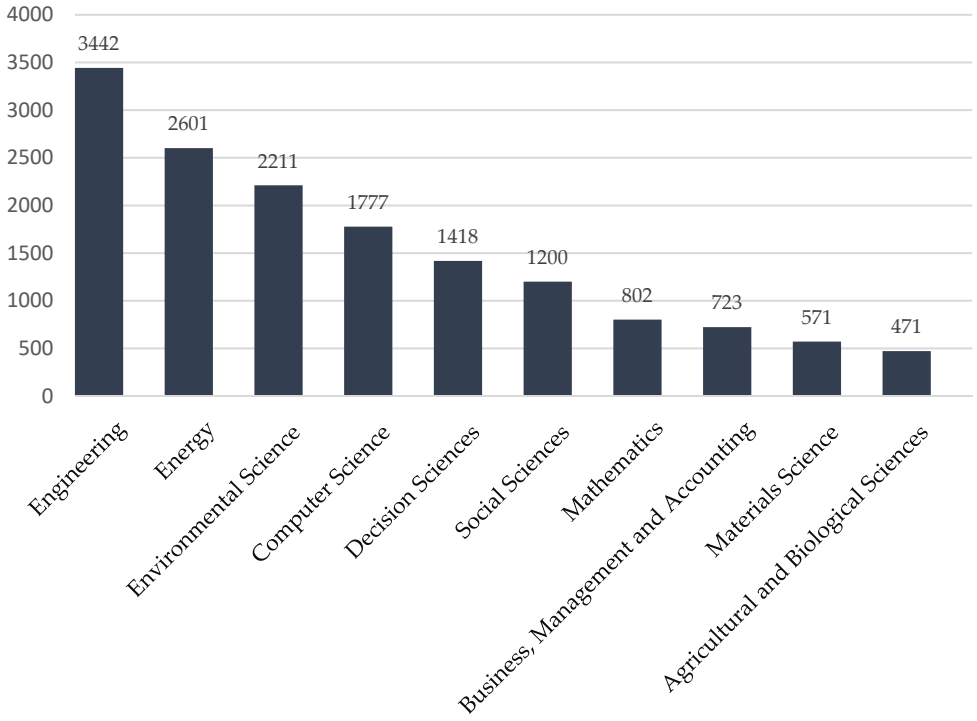

Figure 5. Subject Areas in MCDM Studies—Number of Articles based on Subject Area.

Table 3. List of MCDM Methods.

Method	Number of Results	Method	Number of Results	Method	Number of Results
Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	8241	Fuzzy analytic network process (ANP)	586	Complex Proportional Assessment (COPRAS)	445
VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)	2691	Grey analysis: Grey Relational Analysis/Grey Relational Model (GRA/GRM)	3176	COmbined COmpromise SOlution (CoCoSo)	75
Multi-Objective Optimization by Ratio Analysis (Multi-MOORA)	165	Weighted Sum Model (WSM)	470	Measurement of Alternatives and Ranking according to COmpromise Solution (MARCOS)	35
Multi-Attribute Utility Theory (MAUT)	948	Weighted Product model (WPM)	198	Ranking of Alternatives through Functional mapping of criterion sub-intervals into a Single Interval (RAFSI)	1
AHP	15,452	Aggregated Indices Randomization method (AIRM)	4	Automatic Routine Generating and Updating System (ARGUS) method	3
FST	8730	ANP	3126	Lexicographic Method (LM)	311
Case-Based Reasoning (CBR)	3258	Treatment of the Alternatives according To the Importance of Criteria (TACTIC)	1	Measuring Attractiveness by a categorical Based Evaluation Technique (MACBETH)	162

Table 3. *Cont.*

Method	Number of Results	Method	Number of Results	Method	Number of Results
Data Envelopment Analysis (DEA)	9367	Intercriteria Decision Rule Approach (IDRA)	183	Multicriterion Analysis of Preferences by Pair-wise Actions and Criterion Comparisons (MAPPAC)	3
Simple Multi-Attribute Rating Technique (SMART)	646	Evaluation of Mixed Data (EVAMIX)	65	Multi-Attribute Value Theory (MAVT)	315
Goal Programming (GP)	4113	Passive and Active Compensability Multicriteria ANalysis (PACMAN)	3	Best-Worst Method (BWM)	867
ELimination Et Choix Traduisant la REalité (ELimination Et Choice Translating REality) (ELECTRE)	2782	Dominance-based rough set approach (DRSA)	278	Maximax	195
Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE)	2715	Characteristic Objects METhod (COMET)	102	An acronym in Portuguese for "Interactive Multi-Criteria Decision Making" (TODIM)	249
Simple Additive Weighting (SAW)	976	Evaluation based on Distance from Average Solution (EDAS)	143	Méthode d'ELimination et de CHoix Includent les relations d'ORdre (MELCHIOR)	0
FUZZY TOPSIS	2014	Multi-Attribute Border Approximation Area Comparison (MABAC)	245	MIN_MAX	22
FUZZY AHP	2804	Additive Ratio Assessment (ARAS)	173	Novel Approach to Imprecise Assessment and Decision Environments (NAIADE)	40
Organisation, Rangement Et Synthese De Donnes Relationelles (ORESTE)	35	REGIonal Multicriteria Elimination (REGIME)	217	Ratio Estimation in Magnitudes or deci-Bells to Rate Alternatives which are Non-Dominated (REMBRANDT)	4
Procédure d'Agrégation Multicritère de type Surclassement de Synthèse pour Evaluations Mixtes (PAMSSEM)	6	TACTIC	10	Multi-Attribute Range Evaluations (MARE)	3
Preference Ranking Global Frequencies in Multicriterion Analysis (PRAGMA)	1267	UTilités Additives (UTA)	31	Weighted Aggregated Sum Product Assessment (WASPAS)	270
QUALIty by FLEXible multicriteria method (QUALIFLEX)	117	Decision making trial and evaluation laboratory (DEMATEL)	1378	DEMATEL-based ANP (DANP)	73
Geometrical Analysis for Interactive Aid (GAIA)	68	Induced Ordered Weighted Averaging (IOWA)	125	KANO model/method (author's name)	476

Considering the results of Table 3, a list including 20 more cited methods are given in Table 4. It must be noted that some of the methods have different types (for example ELECTRE I, II, III, etc.); however, the first formats are considered in the table. A short description, and the original references also are provided. As shown in the table AHP, DEA, FST, TOPSIS, and GP are between the main and top cited MCDM methods during 2012–2022 based on the results of the conducted search.

Table 4. Description of the Main MCDM methods.

Method	Description	Original Reference or Underlying Source
AHP	Pairwise comparison of hierarchical criteria considering difference information.	Saaty [16]
DEA	Performance assessment of a set of homogeneous DM units with multiple inputs and outputs.	Charnes and Cooper [17]
FST	Quantifying the linguistic facet of accessible data and preferences to address subjective and ambiguous problems.	Zadeh [18]
TOPSIS	Evaluating based on the distance of alternative to the ideal solution.	Hwang and Yoon [12]
GP	Minimizing the derivation of each objective from the desired target together with optimizing manifold goals.	Charnes and Cooper [19]
CBR	Making recommendations using the analysis of the historical data	Kolodner [20]
GRA/GRM	Dividing information to white, black, and grey (between known and unknown).	Deng [21]
ANP	A non-linear and more general type of AHP using Markov-chain-based aggregation.	Saaty [22]
FUZZY AHP	AHP with the fuzzy evaluation of the alternatives.	Van Laarhoven and Pedrycs [23]
ELECTRE	Outranking the relationship of the alternatives and using pairwise comparison	Benayoun et al. [24]
PROMETHEE	Outranking method (such as ELECTRE) including several iterations.	J.P. Brans [25]
VIKOR	A compensatory version of TOPSIS that is based on minimizing the distance to the ideal solution using a linear normalization approach.	Opricovic [26]
FUZZY TOPSIS	Based on TOPSIS under a fuzzy environment	Chen [27] Or Lai et al. 1994 [28]
DEMATEL	Verifying relationships/interdependence between variables.	Gabus and Fontela [29]
PRAGMA	Comparing partial profiles of alternatives considering all the possible criteria pairs.	Matarazzo [30]
SAW	Involving a simple addition of scores representing the goal achievements considering all criteria that is multiplied by the criteria weights.	Churchman and Ackoff [31]
MAUT	Based on incorporating uncertainty and risk preferences factors into multi criteria decision support methods.	Keeney [32]
BWM	Identifying the best and the worst criteria followed by conducting a pairwise comparisons between each of the best and worst criteria and other ones.	Rezaei [33]
SMART	weighting the criteria based on their importance and converting importance weights into real numbers.	Edwards [34]
Fuzzy ANP	Fuzzy expression of criteria weights in ANP method.	Mikhailov and Singh [35]

5. Summary

MCDM methods are regarded as the main decision-making methods that consider more than one criterion in the decision-making process. This entry aims to discuss the important concepts, applications, and types of MCDM methods. MCDMs are used in different fields and are one of the most common decision-making methods. MCDM methods can be classified considering different aspects. Some of the main classifications are listed, and the main methods are discussed in more detail. The last section investigates the popularity of MCDM methods in different subject areas, and some of the main methods are finally described shortly. Based on the results of this section, MADM methods were focused more than MODM types in different studies, and the AHP method was cited more than other selected techniques.

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