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Survey of Multi-Criteria Decision-Making Methods for Complex Environments

by Justine P Caylor and Timothy P Hanratty

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Survey of Multi-Criteria Decision-Making Methods for Complex Environments

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14. ABSTRACT Decision-making can be a challenge, and that challenge increases in complex environments due to factors such as uncertainty, risk, the sheer amount of information to consider, criticality of time, and severity of the consequence. Multi-Criteria Decision-Making (MCDM) is an invaluable tool that can be used as a decision aid to help determine a favorable solution. This report presents a survey and description of the application of MCDM methods used for problems in complex environments found in literature. Proposed is a taxonomy to assist in determining what MCDM method to select for a specific complex environment.					
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1. Introduction

Decision-making is defined as the process of making choices; it is an inevitable and often times critical component of daily activities (Cambridge Academic Content Dictionary 2017). The act of making a decision often consists of several steps: identifying problems, eliciting preferences, evaluating alternatives, and determining the best alternative (Tzeng and Huang 2011; Sitorus et al. 2019). At a high-level of abstraction, decision-making can be divided into two realms: rational versus intuitive (naturalistic). With rational decision-making, the decision maker is assumed to operate with perfect information and without time constraints, choosing an alternative that maximizes an expected outcome. On the other hand, with naturalistic decision-making, the decision maker is relying on experience to make a decision where the decision space is uncertain, ill-defined, high-consequence, and time constrained (Zsombok and Klein 2014).

That said, decision makers need to have the ability to make decisions by visualizing and comparing different courses of actions and being to answer the “what if” type of questions (Liedtka 1998; Steptoe-Warren et al. 2011). As described by Roy (1981), there are four types of decision problems that a person faces on a daily basis: the “choice” problem, the “sorting” problem, the “ranking” problem, and the “description” problem (Ishizaka and Nemery 2013; Akalp 2017; Sitorus et al. 2019).

Decision-making occurs in noncomplex situations, such as deciding whether to go to a certain restaurant, which flight to book, and what item to purchase on e-commerce (Caylor et al. 2019). In complex situations, such as making a diagnosis in hospitals, determining which problem to handle first in disastrous emergencies, and filtering through operations orders on the battlefield, the process of decision-making becomes challenging due to uncertainty, fast pace, and high risk (Göztepe et al. 2013; Elomda et al. 2014; Hanratty et al. 2017; Etesamipour and Hammell 2019; Németh et al. 2019). Decisions are made from the judgement of various criteria (Aruldoss et al. 2013) that will lead to a solution or a decision over other alternative solutions or decisions. Depending on what is at the decision point, sometimes criteria can change over time, which may affect the optimal solution or decision.

The purpose of this report is to survey the literature of applications of Multi-Criteria Decision-Making (MCDM) methods in complex environments. Section 2 describes the characteristics of complexity. Section 3 introduces MCDM. Section 4 defines seven MCDM methods that are commonly used for complex decision-making research as described in the literature review. Section 5 briefly highlights a review

of the literature. Section 6 discusses the challenge of selecting an MCDM method and present a taxonomy made up of questions that can be used for selecting an MCDM method for decision-making in complex environments. Section 7 consists of concluding remarks.

2. Background

The task of making decisions for real-world problems is already complex, but that level of complexity rises exponentially when the situation involves uncertainty, timeliness, and risk (Ishizaka and Labib 2014). The more criteria that exist for alternatives to consider, the more complex the problem becomes (Aruldoss et al. 2013). Information can be presented and described in different ways with different ranges, such as quantitative and qualitative. The severity of consequence that follows a decision, correct or incorrect, can affect the complexity of the situation. Another thing that adds to the complexity is the fact that these problems are seldom static; they often have dynamic attributes that lead to the consideration of changing alternatives or criteria. Figure 1 describe some of the characteristics that contribute to complexity.

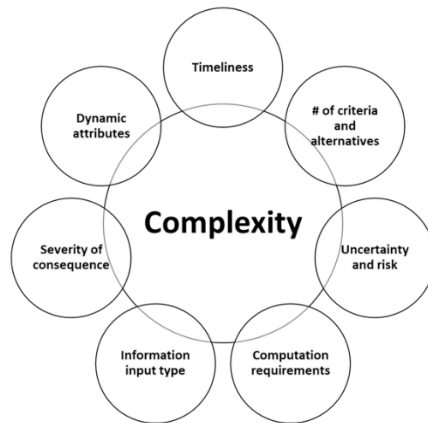


Fig. 1 Complexity characteristics

Examples of dynamic, complex environments are in the field of crime (Wan et al. 2015), disaster relief and evacuation planning (Chan and Armenakis 2014), emergency management and response (Li et al. 2014; De Angel et al. 2019), healthcare (Németh et al. 2019), and the military (Göztepe et al. 2013; Göztepe and Kahraman 2015). To address challenges faced in the decision-making process in such environments, MCDM has been introduced because of its strength in decision-making in complex domains (Aruldoss et al. 2013; Mardani et al. 2015).

3. Multi-Criteria Decision-Making (MCDM)

Since as early as the 1950s (Mardani et al. 2015), MCDM (also referred to as Multi-Criteria Decision Analysis [MCDA]) methods have been an invaluable tool in the decision-making process, especially in complex and uncertain environments. It has grown as a discipline in operations research (Triantaphyllou 2000; Li et al. 2014; Mardani et al. 2015). MCDM models prescribe a way of evaluating, prioritizing, and selecting the most favorable alternative from a set of available ones that are characterized by multiple, usually conflicting, levels of achievement for a set of attributes (Xu and Yang 2001; Campanella and Ribeiro 2011a, 2011b)

MCDM can be broken down into three general stages (Keeney 1982; Roy 1996; Tsoukiàs 2007; Dodgson et al. 2009; Sitorus et al. 2019):

- 1) Structuring a decision problem.
- 2) Determining and applying an MCDM method.
- 3) Determining the final recommendation.

Similarly, Singh and Malik (2014) describe it in eight steps:

- 1) State and define the problem domain.
- 2) Elicit the criteria.
- 3) Screen the alternatives.
- 4) Define the preferences on evaluation criteria.
- 5) Choose the MCDM method for selection.
- 6) Evaluate the MCDM method.
- 7) Apply selected methodology to the problem.
- 8) Evaluate the results.

Numerous methods have been derived and evolved to accommodate various types of situations and applications (Velasquez and Hester 2013). Additionally, there are techniques that can be used to consider problems with quantitative and qualitative factors involved (Mardani et al. 2015). When considering uncertainty, a lot of these methods benefit by also applying fuzzy set theory to its algorithm (Zadeh 1965). This is due to the ambiguity of human decision makers' judgements; oftentimes it is difficult to make a "crisp" decision (Tsaur et al. 2002).

As a way to capture dynamicity, the standard MCDM method has been expanded upon into Dynamic MCDM (DMCDM). DMCDM is the same as standard MCDM,

but it can adapt to different situations using a “retention policy” for historic data/alternatives, using aggregation functions to compute final score/rank using the historic and current data, and it has a “stopping” criteria (Campanella and Ribeiro 2011a, 2011b; Varela and Ribeiro 2014; Arrais-Castro et al. 2015).

When it comes to selecting an MCDM method to consider and implement, there is not a single method that one could use and follow step-by-step to solve any problem (Mardani et al. 2015). Not all problems or situations are the same and may require different computations. In fact, there are many MCDM methods in the field, and it can be difficult to determine what method would be the best method to implement (Aruldoss et al. 2013). Growing in popularity is the process of combining two or more MCDM methods as a way to optimize the strengths of particular methods and make up for any shortcomings, creating a “hybrid” method (Velasquez and Hester 2013).

MCDM can be divided into two categories: Multi-Attribute Decision-Making (MADM) or Multi-Objective Decision-Making (MODM) (Chauhan and Vaish 2012; Singh and Malik 2014; Zavadskas et al. 2014; Mardani et al. 2015). MADM is used to help decision makers assess and compare a finite or discrete number of alternatives, with limited and generally conflicting criteria (Nijssen 2013; Singh and Malik 2014). Some examples of MADM methods are Weighted Sum Model (WSM), Analytical Hierarchy Process (AHP), Technique for Order Preferences by Similarity to Ideal Solutions (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE), Elimination Et Choix Traduisant la REalite’ (ELECTRE), Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR), and Reference Ideal Method (RIM). MODM is focused on the optimization of the multiple objectives of the decision maker, and choices that are composed of continuous criteria are generally infinite or very large. Some examples of MODM are neural networks, goal programming, and genetic algorithms. As described by Nijssen (2013), MADM is more of a “selection process” and MODM a more “design-like” algorithm. In this report, we survey the MADM category of MCDM methods focused on complex decision-making in the literature. Figure 2 depicts a general overview of the MCDM process and methods that are described in this report.

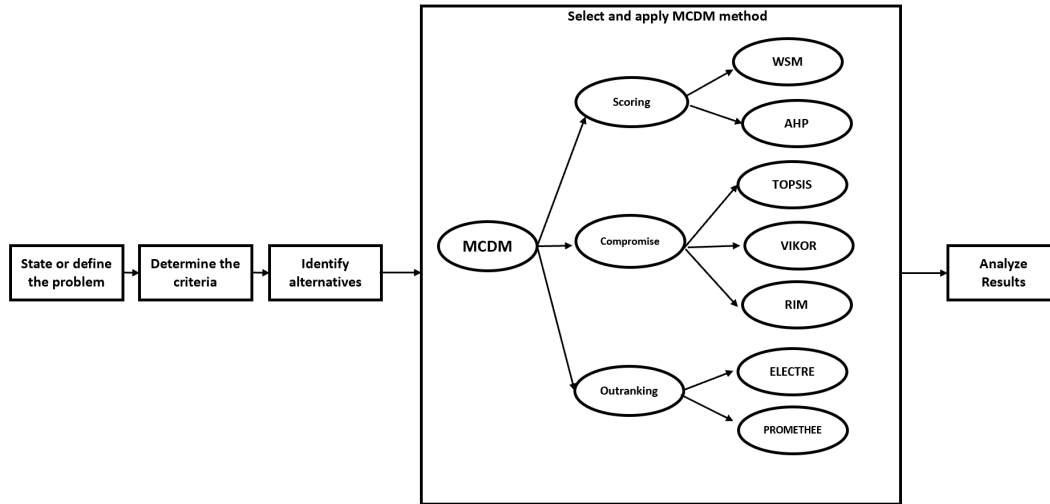


Fig. 2 General MCDM process

4. Methods in MCDM

4.1 Weighted Sum Model (WSM)

WSM (also known as the Simple Additive Weighting [SAW] method) is one of the simplest and earliest MCDM methods (Fishburn 1967; Singh and Malik 2014; Kolios et al. 2016; Mulliner et al. 2016). It is used for evaluating a number of alternatives by adding together criteria values for each alternative and applying the individual criteria weights.

The process of WSM is made up of the following steps (Singh and Malik 2014):

- 1) Identify the potential alternatives.
- 2) Choose the possible criteria that can be used as parameters for determining the best alternative.
- 3) Assign scores to each alternative with respect to each criterion.
- 4) Assign weights to the selected criteria in order to prioritize them.
- 5) Calculate the total score for each alternative corresponding to all criteria.
- 6) The alternative with the highest score is chosen at the optimal solution.

The advantages of WSM consist of strength in single-dimensional problems (Aruldoss et al. 2013), ease of use (Singh and Malik 2014; Kolios et al. 2016), simplistic calculation that does not require complex computation (Velasquez and

Hester 2013), and clear and understandable depiction of prioritized criteria and computation (Singh and Malik 2014).

The disadvantages of WSM are that applicability can be difficult in multidimensional problems (Aruldoss et al. 2013), use can be unrealistic in some cases when attributes vary between qualitative and quantitative or the criterion are not additive (Singh and Malik 2014; Kolios et al. 2016), and results may not be logical (Velasquez and Hester 2013).

4.2 Analytical Hierarchy Process (AHP)

AHP is a method developed by Thomas L Saaty (1977, 1986, 1988) that uses pairwise comparisons and judgments from experts to derive priority measurements (2008). AHP consists of three main parts: 1) decomposing and breaking down the problem into criteria and subcriteria in a hierarchical manner; 2) determining the priorities of the criteria and subcriteria; and 3) synthesizing the priorities to determine which criteria have the highest priority and should be acted upon to influence the problem situation (Saaty 1990a; Kivijärvi and Tuominen 1999; Wan et al. 2015). This allows the decision makers in situations to understand how their judgments can play a role in the decision choice and allows decisions to be made that best suit their goal and understanding of the problem rather than what the “correct” choice is (Wan et al. 2015).

Matrices of pairwise comparisons are formed to estimate the level of importance using numbers from a 1-to-9 AHP fundamental scale (Saaty 2007). Quantitative and qualitative criteria can be evaluated using this scale (Ishizaka and Labib 2014). A consistency ratio (CR) is then calculated to ensure that the comparison matrix is consistent enough to derive priorities (Saaty 1990b; Ishizaka and Labib 2014). If the CR is significantly small (less than 10%), then the estimate of weight is accepted. Otherwise, improvement of consistency is attempted (Saaty 1990b).

Saaty (1990a) describes advantages as follows:

- Consistency: keeping track of the consistency of expert judgements
- Tradeoffs: the ability to take into consideration relative priorities of criteria that allow people to select the best alternative based on their goals
- Synthesis: leading toward the overall estimate of desirability of each alternative
- Judgement and consensus: not insistent on consensus but rather synthesis of a representative outcome from diverse judgments

- Process repetition: enables people to refine their definition of a problem and improve their judgment and understanding through repetition
- Unity: a single, easily understandable, flexible model
- Complexity: integrates deductive and systems approaches to solve complex problems
- Interdependence: interdependence exists between criteria and does not insist on linear thinking
- Measurement: provides a scale for measuring and establishing intangibles and priorities
- The ability to sort elements in an hierarchic structure

Some additional advantages described in literature are the ability to find efficient solutions in simulations (Kivijärvi and Tuominen 1999), the ability to be applied in a variety of contexts (Cheng et al. 1999; Wan et al. 2015), easy extension to fuzzy numbers (Buckley 1985; Rezakhani 2012), and in some applications, low computational requirements (Chang 1996; Cheng 1997).

Some disadvantages of AHP are irregularities in ranking or rank reversal (Aruldoss et al. 2013; Velasquez and Hester 2013), possible information loss when additive aggregation is used (Aruldoss et al. 2013), more pairwise comparisons (Aruldoss et al. 2013), dependency of decision-maker preferences (Dashti 2010; Cui et al. 2011), handling of large amounts of uncertainty and subjectivity of experts (Rezakhani 2012), and some applications requiring high computational requirements (Van Laarhoven and Pedrycz 1983; Buckley 1985; Boender et al. 1989).

4.3 Technique for Order Preferences by Similarity to Ideal Solutions (TOPSIS)

TOPSIS, presented by Hwang and Yoon in the 1980s, is based on the idea of minimizing the distance or determining the shortest distance from the positive ideal solution and maximizing the distance or determining the farthest distance from the negative ideal solution (Hwang and Yoon 1981; Opricovic and Tzeng 2004; Cui et al. 2011; Thor et al. 2013; Singh and Malik 2014). The closeness of the alternatives to the ideal solution is evaluated using Euclidean distance (Aruldoss et al. 2013; Wolfe 2018); by comparing the relative distances, the preference order of the alternatives is determined.

The TOPSIS method comprises the following steps (Opricovic and Tzeng 2004):

- 1) Calculate the normalized decision matrix.
- 2) Calculate the weighted normalized decision matrix.
- 3) Determine the positive ideal solution and negative ideal solution.
- 4) Calculate the separation measures using the n -dimensional Euclidean distance.
- 5) Calculate the relative closeness to the positive ideal solution.
- 6) Rank the preference order.

Some advantages of TOPSIS are that the method is easy to perform and implement (Thor et al. 2013), suitable for large-scale data, precise relative closeness to the positive ideal solution (Thor et al. 2013; Singh and Malik 2014), simplicity (Velasquez and Hester 2013; Singh and Malik 2014), and constant number of steps regardless of the number of criteria to consider.

Some disadvantages of TOPSIS are that Euclidean distance does not consider the correlation of criteria (Velasquez and Hester 2013), judgments are difficult to weight and keep consistent (Velasquez and Hester 2013), normalization by using vector normalization may be dependent on the evaluation unit of a criterion function (Opricovic and Tzeng 2004), problem of rank reversal (Garcia-Cascales and Lamata 2012; Cables et al. 2016; Sánchez-Lozano et al. 2019), and that for the method to work, a maximum and minimum value will need to be identified (Cables et al. 2016; Sánchez-Lozano and Rodríguez 2020).

4.4 Elimination Et Choix Traduisant la REalite´ (ELECTRE)

ELECTRE was first introduced in the 1960s by Bernard Roy as an outranking approach that allows the decision maker to use concordance and discordance indices to analyze the relations between different alternatives and then choose the best one (Aruldoss et al. 2013; Thor et al. 2013; Wolfe 2018). It has evolved into ELECTRE I, II, III, IV, and TRI (Balaji et al. 2009; Thor et al. 2013), and all are based on the same fundamental concepts but differ operationally. For instance, ELECTRE I is used for selection problems, ELECTRE II, III, and IV for ranking problems, and ELECTRE TRI for assignment problems (Aruldoss et al. 2013).

The advantages of ELECTRE are that outranking is used (Aruldoss et al. 2013), it takes uncertainty and vagueness into account (Velasquez and Hester 2013), and it has controlled consistency (Thor et al. 2013).

The disadvantages of ELECTRE are that its process and outcomes can be difficult to explain in layman's terms (Velasquez and Hester 2013), outranking prevents the

strengths and weaknesses of the alternatives from being directly identified (Velasquez and Hester 2013), and it can be time consuming (Aruldoss et al. 2013).

4.5 Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE)

PROMETHEE, developed by Jean-Pierre Brans (Behzadian et al. 2010), is an outranking method similar to ELECTRE. Like ELECTRE, there are many different evolutions of PROMETHEE. Each evolution was identified in the research paper by Behzadian et al. (2010):

- PROMETHEE I is used for partial ranking of the alternatives (Mareschal and Brans 1988).
- PROMETHEE II for complete ranking of the alternatives (Mareschal and Brans 1988).
- PROMETHEE III for rankings based on intervals.
- PROMETHEE IV for complete or partial rankings of alternatives for a continuous set of solutions.
- PROMETHEE V for problems with segmentation constraints (Brans and Mareschal 1992).
- PROMETHEE VI for human brain representation (Brans and Mareschal 1995).
- PROMETHEE Group Decision Support System for group decision-making (Mareschal et al. 1998).
- Geometrical Analysis for Interactive Aid for graphical representation (Mareschal and Brans 1994).
- PROMETHEE TRI for sorting problems (Figueira et al. 2005).
- PROMETHEE CLUSTER for nominal classification (Figueira et al. 2005).

The advantages of PROMETHEE are user friendliness, transparency (Degener et al. 2013), and it does not require the assumption that the criteria are proportionate (Velasquez and Hester 2013).

A disadvantage of PROMETHEE is that it does not provide a clear method on which to assign weights (Velasquez and Hester 2013).

4.6 VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)

The VIKOR method was introduced as a way to solve discrete multi-criteria problems that have noncommensurable and conflicting criteria (Opricovic 1998; Opricovic and Tzeng 2004; Gul et al. 2016). The focus of this method is on ranking and selecting from alternatives, and determining compromise solutions that can help decision makers make a final decision (Opricovic and Tzeng 2007). A compromise solution is the feasible solution that is closest to the ideal solution.

VIKOR comprises the following steps (Opricovic and Tzeng 2004, 2007):

- 1) Determine the best and the worst values of all criterion functions.
- 2) Compute the values of criteria weight, which will express their relative importance.
- 3) Compute the values in relation to “the majority of criteria” (or “the maximum group utility”).
- 4) Rank the alternatives. The results are three ranking lists of S (utility measure), R (regret measure), and Q (index of majority agreement).
- 5) Propose as a compromise solution the alternative that is ranked the best by the minimum measure if the two conditions “acceptable advantage” and “acceptable stability in decision-making” are satisfied.

The advantages of VIKOR are that it is a helpful tool when the decision maker does not know or is unable to provide preference at the beginning (Opricovic and Tzeng 2004), normalized values do not depend on evaluation units of a criterion function (Opricovic and Tzeng, 2004), and the decision maker is able to approve a solution that is closest to the ideal (Opricovic and Tzeng 2007).

The disadvantages of VIKOR are the issue of rank reversal (Cables et al. 2016; Sánchez-Lozano et al. 2019), and similar to TOPSIS, for the method to work, a maximum and minimum value will need to be identified (Cables et al. 2016; Sánchez-Lozano and Rodríguez 2020).

4.7 Reference Ideal Method (RIM)

RIM was developed by Cables et al. (2016) to address the limitations that some MCDM methods such as TOPSIS and VIKOR face when the ideal solution is not always strictly the maximum or minimum value, but rather a value (or set of values) that lie somewhere in between. In RIM, the reference ideal is a value or set of values that fall in the range of the minimum and maximum value.

The procedure of RIM is as follows (Cables et al. 2016):

- 1) Define the work context and establish the range, reference ideal, and weight for each criterion.
- 2) Obtain the valuation matrix in correspondence with the defined criteria.
- 3) Normalize the valuation matrix with the reference ideal.
- 4) Calculate the weighted normalized matrix.
- 5) Calculate the variation to the normalized reference ideal for each alternative.
- 6) Calculate the relative index of each alternative.
- 7) Rank the alternatives in descending order. The alternatives at the top constitute the best solutions.

The advantages of RIM are that it does not face rank reversal, it is a better approach (than TOPSIS and VIKOR) to changes in the data, and it allows for an ideal alternative to being either a specific value or between maximum and minimum values (Cables et al. 2016; Sánchez-Lozano and Rodríguez 2020).

The disadvantages of RIM are the subjectivity nature of setting the reference ideal value from experts (Sánchez-Lozano and Rodríguez 2020) and that a reference ideal must be determined in order for this method to be used.

In literature, it was clear that the hybrid method of AHP and TOPSIS is popular and commonly applied. Recent literature has shown that there are hybrid method applications of AHP and RIM (Sánchez-Lozano et al. 2019; Sánchez-Lozano and Rodríguez 2020).

Table 1 summarizes the advantages and disadvantages of MCDM.

Table 1 MCDM advantages and disadvantages summarization

MCDM method	Advantages	Disadvantages
WSM	<ul style="list-style-type: none"> • Strong in single-dimensional problems • Easy to use • Calculation and computation are simple • Clear and understandable 	<ul style="list-style-type: none"> • Difficult in multidimensional problems • Unrealistic in some cases • Results may not be logical
AHP	<ul style="list-style-type: none"> • Consistency • Flexible and understandable model • Interdependence between criteria • Hierarchical structure • Can handle quantitative and qualitative criteria • Allows for judgments to be refined • Can be applied to various contexts • Easy extension to fuzzy numbers 	<ul style="list-style-type: none"> • Irregularities with rank reversal • Information loss is possible • Handling of large amounts of uncertainty and subjectivity • High computational requirements • Dependency on decision-maker preferences
TOPSIS	<ul style="list-style-type: none"> • Easy implementation • Suitable for large-scale data • Simplicity • Constant number of steps in process 	<ul style="list-style-type: none"> • Euclidean distance does not consider the correlation of criteria • Consistency • Vector normalization may be dependent on the evaluation unit of a criterion function • Problem of rank reversal • Identification of maximum and minimum value are required
ELECTRE	<ul style="list-style-type: none"> • Takes uncertainty and vagueness into account • Controlled consistency 	<ul style="list-style-type: none"> • Process and outcomes can be difficult to explain • Outranking can cause strengths and weaknesses of the alternatives not to be identified • Time consuming
PROMETHEE	<ul style="list-style-type: none"> • User friendliness and transparency • Does not require the assumption that the criteria are proportionate 	<ul style="list-style-type: none"> • Does not provide clear method on which to assign weights
VIKOR	<ul style="list-style-type: none"> • Helpful when preference is not known or provided at beginning • Normalized values do not depend on evaluation units • Decision maker is able to approve solution closest to ideal 	<ul style="list-style-type: none"> • Problem of rank reversal • Identification of maximum and minimum value are required
RIM	<ul style="list-style-type: none"> • Does not face rank reversal • Can handle changes in the data • Allows for an ideal alternative to being either a specific value or between maximum and minimum values 	<ul style="list-style-type: none"> • Subjectivity from experts • Reference ideal must be determined in order for this method to be used

5. Literature Review of MCDM Applications

Campanella and Ribeiro (2011a, 2011b) describe an extension to the classic MCDM model by creating a framework for a dynamic MCDM model, as most decisions made in the real world are dynamic and may require many contextual considerations before coming to a conclusion. Classic MCDM is typically modelled in a matrix representing the attributes' level of achievement of that particular alternative from a scale of 0 to 1, 0 meaning no satisfaction and 1 meaning complete satisfaction. The resulting value after evaluation using an aggregation function represents how preferable the associated alternative is ranging from 0 (no preference) to 1 (strongest preference). In the dynamic MCDM model for a given situation/scenario, a set of alternatives are considered and evaluated on their priority/preference. In DMCDM, there are three possibilities of retention policies: 1) accumulate alternatives; 2) select the k alternatives, which rank higher than all others; and 3) select all alternatives whose evaluation surpasses some threshold. The dynamic decision process also may require a stopping method if it makes sense to the situation, as in a method that completes the run of iterations. Several examples are described and recommended for the DMCDM model, such as picking a site for landing a helicopter among nine possible choices, determining which patient cases to prioritize based on clinical need, diagnosing diseases, providing emergency disaster relief, determining which planetary landing site is most optimal, and considering which external supplier should be selected.

Varela and Ribeiro (2014) describe using DMCDM to support collaborative manufacturing scheduling systems and to help with manufacturing scheduling problems in business settings. The dynamic environment in this case is distributed and collaborative. In these contextual scenarios, this is a temporal MCDM problem of determining preference in respect to manufacturing resources; the problem is resolved by ranking and selecting the resources for manufacturing scheduling. Each resource is evaluated using certain criteria (lack of reliability, speed, time, and costs), and in this case, the value scores represent penalty. The lower the value score, the better and more optimal in rank the resource is. Aggregation is done using a simple weighted sum.

Arrais-Castro et al. (2015) propose a negotiation process method using DMCDM for selecting business partners or suppliers in collaborative, networked organizations. The negotiation process includes using specialized software agents that work together to achieve goals—Order Agents, Project Management Agents, and Production Management Agents. Due to the changeable context of selecting business partners or suppliers, the DMCDM ranks them using past, present, and future information.

Benítez et al. (2012) use the MCDM method AHP to make decisions in a dynamic context. The authors describe AHP as “used to construct coherent aggregate results from preference data provided by decision makers”. Having users come up with input for certain criterion in decision-making spaces, especially dynamic ones, can be a challenge. That being said, the authors propose a framework that allows users to provide partial and/or incomplete preference data at different given times. The algorithm used in the framework will determine the new priority vector from the users' new input. The proposed framework was applied in practice in a suitable leak control policy in urban water supply. The criteria that fed into this method were planning development cost and its implementation, budget and credits, investment retrieval, environment cost, and social cost.

Sarraf and McGuire (2018) developed Safe Route Planner, a system that allows users to plan traffic routes and detect any hazards that would make the route dangerous. Some of these hazards that can lead to car crashes can be identified as geometric characteristics, bad visibility, high speed limit, traffic volume, or common appearances of animal crossings. There are many important factors to consider, and the usage of historic accident data and open-source maps can help find the safest roads. The former system used only fatal crash data, and it was difficult to calculate the safety levels of roads. This report notes updates to the Safe Route Planner, including the incorporation of real crash data and open-source maps; developing a weight calculation method and a color-coding system to visualize safety levels; and estimating daily traffic counts and residential and high curvatures avoidance methods. The Safe Route Planner was evaluated against Waze and Google Maps and resulted in similar path suggestions and better options. Sarraf and McGuire (2020) extend their research by implementing various MCDM algorithms in a comparative study. Due to the challenge of the user having to make decisions between different route alternatives of shortest, fastest, or safest, the MCDM algorithm is to aid in the decision-making process in consideration to multiple criterion. The different MCDM algorithms selected for this study were AHP, Fuzzy AHP, TOPSIS, Fuzzy TOPSIS, and PROMETHEE. Different evaluation metrics were used and compared as well, including Spearman's rank correlation coefficient, average overlap, and discounted cumulative gain. Two case studies are conducted for evaluation. The first case study results reveal that alternative D is the best path and that the ranking results of AHP and PROMETHEE were identical. The second case study reveals that alternative C or D could be selected as the best path (due to little differences between them in scoring) and that the ranking results for AHP, fuzzy AHP, and PROMETHEE were identical. TOPSIS and Fuzzy TOPSIS produced poor ranking results in both case studies. AHP is generally chosen as a method rather than PROMETHEE due to PROMETHEE requiring the importance weights to be known, whereas AHP derives the weights. Discounted cumulative

gain was determined to be the most suitable evaluation method for both case studies.

Göztepe et al. (2013) focus on improving the military logistics decision-making process by analyzing among other decision-making processes used in the field. The Analytical Network Process is determined to be the most appropriate method and is used for a sample model for military logistics. The goal is selecting the best course of action (COA) out of three alternatives from which to choose. The criteria used are Principle of War1, Principle of War2, Sustainment, and Operation.

Göleç et al. (2016) implement and compare different MCDM algorithms for the case study of evaluating which military cargo aircraft is the best alternative. The different algorithms described in this paper are AHP, SAW, ELECTRE, and TOPSIS. The criteria for evaluating among the alternatives are operational effectiveness, the country's share in the project, maintainability, maintenance easiness, and cost-effectiveness. All algorithms have an advantage of being able to handle qualitative and quantitative data. The results reveal that all of the algorithms except for ELECTRE selected the same alternative as the most suitable.

Göztepe and Kahraman (2015) suggest implementing an MCDM algorithm into the Military Decision-Making Process (MDMP) to generate a new MDMP. This proposed approach framework has five steps:

- 1) Receipt of mission
- 2) Mission analysis
- 3) COA development and analysis applying MCDM
- 4) Comparison of COA alternatives
- 5) Approval of a COA

There are several different MCDM algorithms that could be used, and the case study presented in Göztepe and Kahraman (2015) uses AHP to help calculate the weights for four alternatives using the criteria of suitability, feasibility, acceptability, distinguishability, and completeness.

Németh et al. (2019) assessed eight criteria weighting methods to understand the advantages and disadvantages of the different methods for selecting a methodology for decision-making in low- and middle-income environments. The researchers evaluated the following methods: direct rating, swing weighting, the simple multi-attribute rating technique (SMART), AHP, the measuring attractiveness by a categorical-based evaluation technique (MACBETH), discrete choice experiments (DCEs), potentially all pairwise rankings of all possible alternatives (PAPRIKA)

methodology, and conjoint analysis (CA). A qualitative assessment of resource requirement, software requirement, chance of bias, and general complexity was completed for each method. Results indicate that higher levels of general complexity may also come with less potential for bias, but that comes with increased resource intensity and participant burden. Across the eight assessments, SMART and AHP are determined to be potentially the most feasible methods for decision-making in low- and middle-income environments.

Turskis et al. (2019) propose a model for calculating risks of information infrastructure by implementing a hybrid MCDM approach using an Integrated Delphic-Eckenrode's Likert-type Scale-based Fuzzy Rating and AHP. The proposed method allows for group decisions in two environments. A set of alternatives are formed, five threats are identified as criteria (health and safety, technology, information security, legal and regulatory compliance, and climate and weather), and six characteristics are identified as subcriteria (loss of availability, loss of confidentiality, loss of integrity, direct losses, indirect losses, and criticality). The researchers describe that the model is a suitable method for determining the probability of risk and impact or determining the importance of criteria.

Haddad and Sanders (2018) present a new framework to recommend an MCDM method from a set of candidate methods when considering risk and uncertainty. A method is recommended based on the best compromise in minimum percentage change required in inputs to change the ranking of alternatives. Three decisional problems were used as numerical examples for the novel framework that was evaluated on six scenarios: three that depended on human decision makers and three that depended on performance measures and criteria weights. AHP and PROMETHEE II were compared on stability of the outcome in consideration to uncertainty that affects criteria weight and performance measures.

Ishizaka and Labib (2014) propose a hybrid approach comprising four methods to evaluate and prevent disasters by optimizing safety. The four methods are problem structuring to build a hierarchy of issues leading to a disaster; Crisis Tree Analysis to graphically display the events that may lead to an accident and Reliability Block Diagram for system functionality and critical component visualization; AHP to quantify the occurrence of events; and knapsack resource allocation that optimizes the safety measures for each event. This novel hybrid method can not only be used to prevent disasters but can also be applied to other fields for determining costs.

Rajabi et al. (2020) utilized the fuzzy Delphi method and fuzzy AHP to identify and prioritize the occupational stressors among firefighters. The study was qualitative-descriptive in nature. The fuzzy Delphi method helped identify the most important

stressors, and then fuzzy AHP weighted and prioritized the identified stressors. Fifty-two occupational stressors were identified among four main dimensions (managerial and organizational; operations; personal; and interpersonal). Results revealed that managerial stressors had the highest weight when compared with the other dimensions for firefighters.

Degener et al. (2013) created a multi-criteria facility location model using PROMETHEE I and II and sensitivity analysis to determine the best warehouse location to stock emergency relief supplies in the pre-disaster phase of a natural disaster. This model was tested in a case study in a flood-prone area of Bangladesh.

In a study that investigates how to reduce wait times of patients of the Emergency Department of a governmental hospital in Tehran, Iran, Eskandari et al. (2011) propose a framework that implements Group AHP and TOPSIS. Fourteen different scenarios are suggested for reducing bottlenecks. Group AHP is used in this study to identify various criteria and subcriteria and then assess their relative importance to determine priorities. TOPSIS is then used by taking the weights calculated from the previous MCDM method and ranking the improvement scenarios. The results from this study show that the average time can be reduced 42.3% with the optimal scenario selected.

Chan and Armenakis (2014) use MCDM, specifically AHP, to model risk and aid in evaluating the optimal evacuation route out of the alternatives. A 3D building evaluation route model and visualization was developed and demonstrated using three test scenarios. The criteria that feed into the AHP method were distance, risk level, and congestion.

Moghadas et al. (2019) conduct a study for assessing the urban flood resilience in Tehran, Iran, by selecting a baseline resilience indicator for community (BRIC) framework and hybrid MCDM methodology. The BRIC framework encompasses six dimensions of social, economic, institutional, infrastructural, community capital, and environmental elements. Indicators/criteria of each dimension for the different districts are identified, and the sentiment of their impact is determined. Any criteria that were highly correlated after using Pearson Correlation Coefficient were removed to address issues of multicollinearity. AHP is then used to conduct pairwise comparisons of the criteria and calculate normalized weights. TOPSIS takes the weights calculated from AHP and then calculates the weighted normalized decision matrix. Each district is measured by relative closeness to the positive and negative ideal solutions. This will lead to a ranking of the urban districts from highest to lowest flood resilience. The results produced from the application of these methods are mapped visually into six resilience domain maps, as well as an overall disaster resilience map. The findings from this research can lead towards

integrating disaster resilience into urban planning and help with identifying possible hotspots that should be considered for disaster risk management.

As described by researchers Sarabadan and Abbasi (2015), evaluating tactical missile systems is an MCDM problem. Thus, in their paper, they describe doing so using fuzzy AHP and fuzzy TOPSIS. The proposed model comprises three parts. First, criteria are identified that will be used in the model. In this study, there are five tactical missile system alternatives and six criteria (effective range, guidance system, warhead, speed, price, and production capacity). Second, AHP is used to calculate the weights of the criteria. Finally, missile systems are evaluated using fuzzy TOPSIS and will determine a ranking to find the best missile system. Results revealed the unweighted ranking of the missile systems to be M1, M2, M4, M3, and M5 and weighted ranking of M1, M2, M5, M3, M4. Regardless, M1 is still determined to be the best missile system.

Sánchez-Lozano and Rodriguez (2020) conducted research on what the best combination of methods would be for decision-making problems in the Spanish Air Force. This study specifically focused on the problem of selecting the best military advanced training aircraft, with criteria of both qualitative and quantitative natures. AHP is implemented to determine criteria weights, and a novel methodology of Fuzzy RIM allowed them to compare the set of alternatives of four advanced training aircrafts based on an ideal reference alternative. Sensitivity analysis compared with other MCDM methods (TOPSIS, WSM, and a revised version of AHP) was conducted to ensure consistency in results. Results of the sensitivity analysis indicated that the method was consistent and robust. In literature, the combination of fuzzy AHP and fuzzy TOPSIS is extensive due to the ability to analyze quantitative and qualitative criteria; however, the authors chose to combine AHP with fuzzy RIM. They note that the mathematical foundations of TOPSIS may not be suitable for solving decision-making problems in which the ideal alternative does not require a maximum or minimum criterion. The RIM method allows for quantitative or qualitative criteria values to fall within an interval range rather than the ideal values needing to be maximums or minimums when evaluating alternatives. Fuzzy RIM can be used to solve problems that may be vague or imprecise.

The study by Wan et al. (2015) implements AHP to calculate the weights of criteria that evaluate crime factors of alternatives to pedestrian walking routes, and create a framework that integrates AHP and Google Maps. The criteria that have influences on the safety walking is distance, visibility, and obstacles. A rank of the best path to worse path in terms of safety will result from this framework.

Sánchez-Lozano et al. (2015) evaluate combining the MCDM methods with fuzzy logic for the decision-making problem in the Spanish Air Force of selecting the best military training aircraft. AHP is used to calculate the weights of the qualitative and quantitative criteria for each aircraft alternative, and TOPSIS is used to provide a ranking of the alternatives. There was 12 criteria for five alternative aircrafts (Pilatus PC-21, Beechcraft T-6C, PZL-130 Orlik [TC-11], KT-1 Basic Trainer, CASA C.101 Aviojet), and the best alternative was determined to be the Pilatus PC-21.

Sanchez-Lozano et al. (2019) describe combining two MCDM methods, AHP and RIM, to provide a ranking of Near-Earth Asteroid (NEA) impact dates. Several NEA features were considered as criteria to be used to rank the alternatives, such as distance to Earth, width, stretch line of variation, impact probability, and impact energy. Weights of the criteria were determined by an AHP-based approach, and the list of impact dates were assessed using RIM. A triple sensitivity analysis was conducted to test the robustness of the results.

Kocaman's master's thesis (2009) focused on establishing a suitable and feasible assessment methodology based on MCDM methods to derive Operational Readiness Level through Material Readiness Level for the naval forces. The main three steps in the research are normalization, weighting, and ranking. Examples of some methods used were AHP and Data Envelopment Analysis (DEA). Some conclusions made from this study were that AHP proved to be inefficient when it comes to alternative comparisons if there was a large number of alternatives and criteria. However, AHP is useful for getting the weights. DEA was deemed not suitable due to not being able to predict the efficient warships in the case study compared to overall rankings.

Battin and Bender (1992) described a lack of direction within the Air Force for conducting economic analyses. The research completed in this thesis was focused on exploring an alternative method for conducting economic analyses involving qualitative factors, and multiple criteria decision-making was selected. Specifically, AHP was selected as the method to apply as it was deemed the most promising technique to rate projects on a ratio scale. Expert Choice was an effective software tool that was used to help complete the analysis; it was recommended that the Air Force should acquire a software version of the AHP.

Benfares et al. (2019) present a framework for automatically monitoring and predicting the level of depression in cancer patients using MCDM method AHP and data from the Center for Oncology and Hematology of the University Hospital Center Mohammed VI in Marrakech to extract the criteria. The goal is to help clinicians select the best decision, ensure a better follow-up with patients, and

reduce the suffering of the disease. The proposed framework has three main phases: 1) the collection of diagnostic criteria, 2) treatment of symptoms based on AHP, and 3) decision-making-based evaluation alternatives. After an experimental case study, results revealed to be accurate and consistent.

Daoud et al. (2018) propose a multi-criteria recommendation method to identify accurate prediction algorithms according to the input data available, which means that for every iteration, a different algorithm may be selected to reach optimal accuracy. The goal is to create an approach that improves the accuracy of predicting the sensitivity of cell lines to anti-cancer drugs. The proposed method is called MCRM4Pred; it takes in heterogeneous input representing characterization of the tumor cell lines coupled with the recommended drug for treatment, and then ranks the algorithms and recommends the most adequate one. AHP is used to determine the importance of each criteria, and TOPSIS is used for ranking. MCRM4Pred is compared to state-of-the-art prediction algorithms IntegratedMRF and KBMTL, and results reveal MCRM4Pred performs better than the other two algorithms.

Kaymaz and Dirı (2008) describe the complicated nature of the source selection phase in the government acquisitions due to the involvement of MCDM and subjectivity. The goal of this research was to demonstrate the current method that the US Air Force was using for source selection, a color rating method, was flawed and that the MCDM method WSM performs better in comparison. The authors selected WSM out of the numerous other MCDM methods due to the simplicity of the model and ease of understanding. To evaluate the two models, the color-rating model and the quantitative WSM, a scenario using the KC-X Tanker Replacement Program was used. A second version of both models that made some changes to the color/adjectival ratings and numerical ranges was evaluated. Overall, results revealed that both models selected different winners for the KC-X program, and that the color rating method is not capable of showing small differences. It is recommended that the color rating method be redeveloped with an increased number of color and adjectival ratings instead of a limited number of ratings in order to increase its sensitivity.

6. Discussion

Upon conducting a literature review on the application of MCDM methods in complex environments, it was evident that many different methods can be used, depending on the situation at hand. If one method is applicable to one situation, it does not necessarily mean that it is applicable or ideal for a different situation. Generally speaking, the WSM MCDM method was observed in research in low-complexity environments, whereas Fuzzy Hybrid methods were undertaken in

environments that are highly complex (Fig. 3). AHP, TOPSIS, ELECTRE, PROMETHEE, VIKOR, and RIM fall in the moderate level of complexity, and depending on the context of the situation, can be used in lower- or higher-complexity environments. It can be difficult to differentiate which method is more suitable than the other when it comes to handling complex situations. All of the methods have advantages and disadvantages.

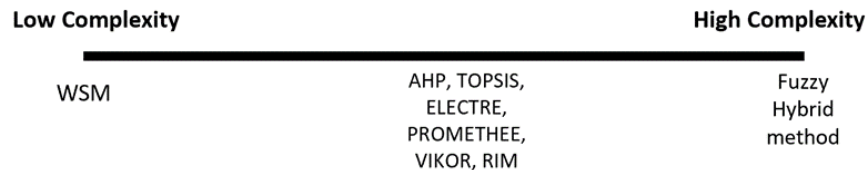


Fig. 3 MCDM methods on the complexity scale based on the literature review

Important questions that need to be asked in any research utilizing an MCDM are which MCDM method to select and how to make that selection. Various researchers (Kornysheva and Salinesi 2007; Roy and Słowiński 2013; Cinelli et al. 2014; Saaty and Ergu 2015; Zandebasiri and Pourhashemi 2016; Haddad and Sanders 2018; Wątróbski et al. 2019a, 2019b; Munier 2019; Bajec and Tuljak-Suban 2019; Cinelli et al. 2020) have analyzed characteristics and questions that can aid in the MCDM selection process. Munier (2019) generated an interactive tool for selecting an MCDM method. Bajec and Tuljak-Suban (2019) proposed a framework for comparing various MCDM methods and choosing the best one for the case of selecting a third-party logistics provider. Wątróbski et al. (2019a, 2019b) described their innovative tool for selecting an MCDA method based on the decision problem. Cinelli et al. (2020) present a taxonomy of the MCDA process characteristics as a hierarchical structure that breaks everything down into three main phases (problem formulation, construction of the decision recommendation, and qualitative features and technical support) and 10 main characteristics (problem type, criteria, elicitation of preferences, features of aggregation, exploitation of the preference model, easiness of method's use, processing time needed to compile the data required for the method, number of alternatives and/or criteria the method can work with, extent of use of the method in the specific context/area, and software support and graphical representation). Based on the MCDA taxonomy framework by Cinelli et al. (2020), the framework by Bajec and Tuljak-Suban (2019), the interactive tool by Munier (2019), the MCDA innovative tool by Wątróbski et al. (2019a, 2019b), the selection questions described in literature, and the characteristics of complexity (see Section 2), this report proposes a taxonomy of 11 questions to consider when selecting an MCDM method for a decision-making problem in complex environments (Fig. 4). The seven MCDM methods highlighted

in this report were applied to the taxonomy based on how the MCDM methods were described through the literature review.

The 11 questions are as follows:

- 1) What type of method is of interest?
- 2) Can the MCDM method calculate criteria weight?
- 3) What type of criteria preference types are supported?
- 4) Into what type of measurement scale are the criteria input?
- 5) Can the MCDM method handle uncertainty?
- 6) Is there software support for the MCDM method?
- 7) What is the ease of use for the MCDM method?
- 8) What is the processing time/computation power required for the MCDM method?
- 9) How many criteria and alternatives need to be considered for the decision problem for the method to work best?
- 10) What is the type of output results?
- 11) Does the MCDM method allow for sensitivity analysis to be performed to evaluate for robustness?

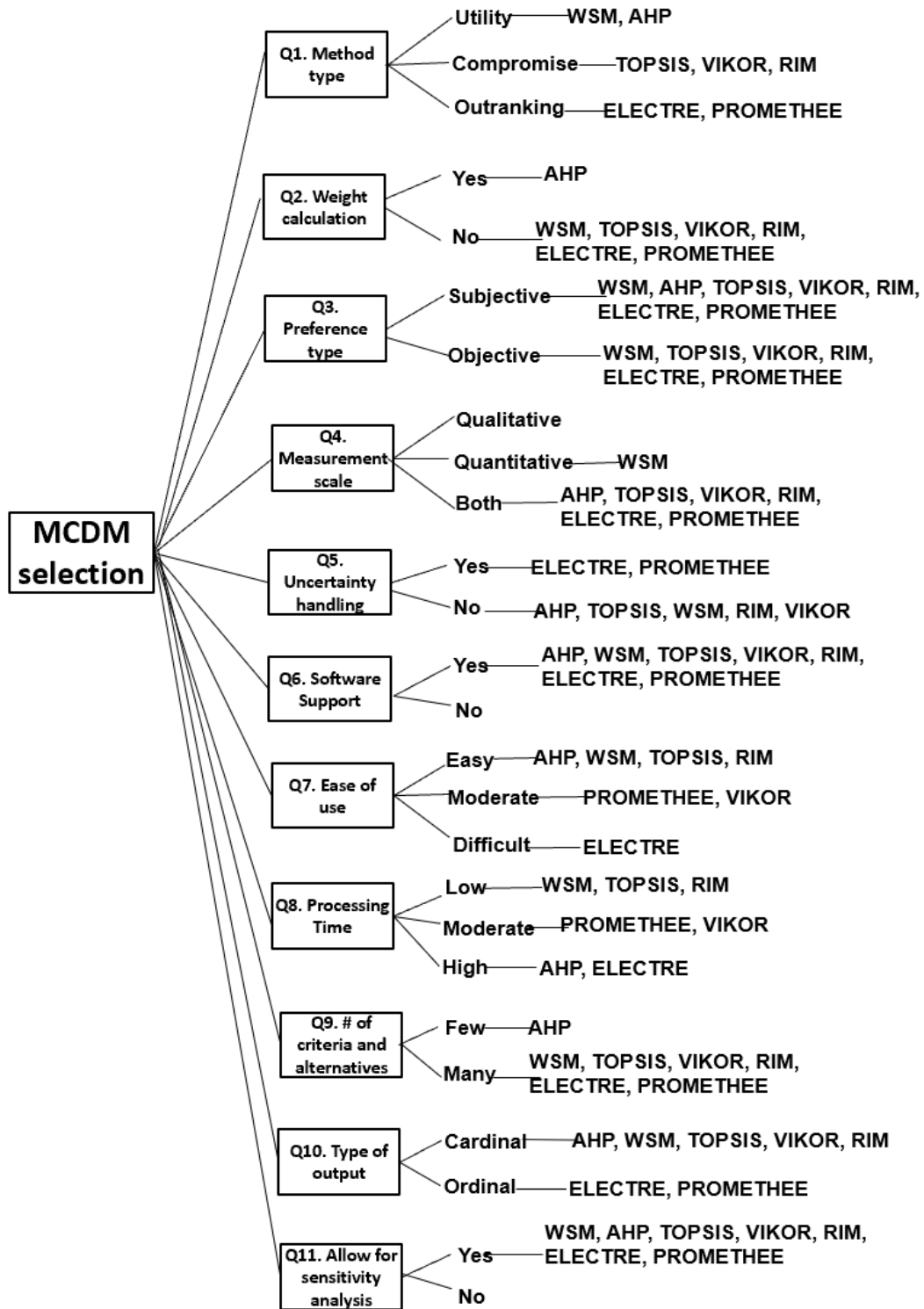


Fig. 4 MCDM question taxonomy

7. Conclusion

Decision-making can be an extremely daunting task due to complex characteristics that can define the problem. MCDM can be used as a helpful decision aid that can help evaluate, prioritize, and select favorable alternatives from a set of available alternatives that are characterized by criteria, often conflicting. This report surveyed applications of MCDM in complex environments, and seven methods (WSM, AHP, TOPSIS, VIKOR, ELECTRE, PROMETHEE, and RIM) were commonly used. The application of hybrid methods was also very popular in the literature review, which aims to work upon the strengths of two or more MCDM methods and diminish their weaknesses. After the literature review, it became very apparent that there are many suitable methods for complex environments, and selecting one can be challenging. To address this challenge, work is ongoing in the field with questions and taxonomies to help in the selection process. An MCDM taxonomy of 11 questions—inspired by the taxonomy presented by Cinelli et al. (2020), the interactive tool by Munier (2019), the framework by Bajec and Tuljak-Suban (2019), the MCDA innovative tool by Wątróbski et al. (2019a, 2019b), the selection questions described in literature, and the characteristics of complexity—is proposed to help with the MCDM selection process in considerations to complex environments.

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List of Symbols, Abbreviations, and Acronyms

AHP	Analytical Hierarchy Process
BRIC	Baseline Resilience Indicator for Community
CA	conjoint analysis
CR	consistency ratio
COA	course of action
DCE	discrete choice experiment
DEA	Data Envelopment Analysis
DMCDM	Dynamic Multi-Criteria Decision-Making
ELECTRE	Elimination Et Choix Traduisant la REalite´
MACBETH	Measuring Attractiveness by a Categorical Based Evaluation Technique
MADM	Multi-Attribute Decision-Making
MCDA	Multi-Criteria Decision-Analysis
MCDM	Multi-Criteria Decision-Making
MDMP	Military Decision-Making Process
MODM	Multi-Objective Decision-Making
NEA	Near-Earth Asteroid
PAPRIKA	Potentially All Pairwise Rankings of All Possible Alternatives
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluations
RIM	Reference Ideal Method
SAW	Simple Additive Weighting
SMART	Simple Multi-Attribute Rating Technique
TOPSIS	Technique for Order Preferences by Similarity to Ideal Solutions
VIKOR	Vlsekriterijumska Optimizacija I Kompromisno Resenje
WSM	Weighted Sum Model

1 DEFENSE TECHNICAL
(PDF) INFORMATION CTR
DTIC OCA

1 CCDC ARL
(PDF) FCDD RLD DCI
TECH LIB

2 CCDC ARL
(PDF) FCDD RLC IT
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