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The Role of Fuzzy Set Theory in Enhancing Multi-Criteria Decision-Making Models

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Abstract

This study explores the integration of fuzzy set theory with multi-criteria decision-making (MCDM) techniques to enhance decision-making frameworks for complex problems. While traditional multi-attribute decision-making (MADM) focuses on discrete issues and multi-objective decision-making (MODM) addresses continuous challenges, this research aims to bridge these methodologies by incorporating advanced fuzzy logic concepts. The use of type-2 fuzzy sets, intuitionistic fuzzy sets, and neutrosophic sets allows for a more nuanced understanding of human cognition, particularly in dealing with uncertainties such as hesitancy and indeterminacy. By applying these fuzzy constructs, the study seeks to improve the flexibility, robustness, and human-centric nature of decision-making processes across various fields, including engineering, management, finance, healthcare, environmental science, and artificial intelligence. The increasing scholarly interest in MCDM reflects a collective effort to refine decision-making strategies, acknowledging the complexities and ambiguities inherent in human judgment. Overall, this research contributes to the ongoing evolution of decision-making frameworks, emphasizing the importance of adapting to the intricacies of real-world scenarios.

Keywords: Fuzzy, Multi-Criteria, Models, Theory And decision

Introduction

Multi attribute decision making (MADM) approaches deal with discrete MCDM issues, while multi objective decision making (MODM) approaches deal with continuous MCDM problems. By utilizing linguistic values represented by fuzzy numbers, fuzzy MCDM models allow either a single decision maker or a committee of decision makers to evaluate alternatives in relation to predetermined criteria, taking into account the relative importance of each criterion and the alternatives' suitability in comparison. Values of linguistic variables may be words or phrases in any language, whether it's natural or artificial. To address fuzzy MCDM issues, many methods have been suggested. You may get a comparison and overview of several of these approaches in and. In fuzzy multi-criteria decision-making, Abdullah gives a quick overview of categories and explains its early and current uses. A number of practical examples are given to illustrate the concept of category in fuzzy multi-criteria decision-making and its uses. Recent work has expanded fuzzy set theory by creating new varieties of fuzzy sets.

Some examples of fuzzy sets are type-n and type-2 fuzzy sets, which include membership function uncertainty in their definitions, nonstationary fuzzy sets, which add a connection to the membership functions to represent small variations in the membership function, fuzzy multisets based on multisets that allow elements to be repeated, and hesitant fuzzy sets (HFS), which are a new and intriguing extension of fuzzy sets introduced by Atanassov. When an element's membership function can be defined using a collection of values, HFS become quite handy. A more robust method of linguistic elicitation has recently been suggested, using hesitant fuzzy linguistic term sets (HFTLS). The term "decision-making" refers to the process by which a group of individuals seeks to solve an issue in a way that will allow them to achieve a desired outcome more effectively than other approaches. Every branch of research has its fair share of decision-making challenges, including the hard sciences, medicine, and engineering. Making a choice is quite challenging because of all the things that go into it. In these complicated situations when choosing the optimum option is quite challenging, multi-criteria decision-making (MCDM) offers strong judgments by using the fundamental principle of symmetry to balance the arrangement where parts or characteristics have an equal or comparable distribution.

The MCDM's symmetry checks bias and maintains equity by equating the relative importance of each criterion. This level of fairness eliminates prejudice and promotes open decision-making. By making it possible to compare options fairly across many criteria, symmetry encourages logical decision-making. Incorporating symmetry into MCDM frameworks allows decision makers to quickly analyze and compare choices in many applications, such as project selection, efficient planning, and resource allocation. From transportation and investments to military and engineering, from biology and economics to agriculture and health, and even environmental research, MCDM is essential in many areas of life. Multi-criteria decision-making (MCDM) is an open and organized approach that permits reasonable selection between alternatives according to a set of criteria. The use of MCDM, however, is not without its share of ambiguity and uncertainty in the actual world.

Literature Review

Numerous studies using classical fuzzy sets (type-1) to analyze stock market time series have been published. Having said that, type-1 fuzzy sets aren't very descriptive, thus they can't handle all the unknowns in stock market developments. This research addresses a knowledge vacuum in the field by examining the usage of type-2 fuzzy logic in financial markets. Additional uncertainty in Type-2 fuzzy sets might arise from financial data that is ambiguous, uncertain, or erroneous and used to construct model inputs. We contrast the type-1 fuzzy model with four proposed techniques based on type-2 fuzzy logic, which vary in the amount of uncertainty included in fuzzy sets. The purpose of this case study is to provide data that can be used to build an ETF investing model for use with ETFs traded on global stock exchanges. There is a comparison between the type-1 traditional fuzzy logic model and the type-2 models that have been developed. Type-2 fuzzy logic with dual fuzzy sets outperforms other methods in accurately describing financial time series data and producing reliable findings, according to the comparison. The outcomes validate the competence and efficacy of the strategy put out in this report. Type-2 fuzzy logic models, on the other hand, perform worse when uncertainty levels in fuzzy sets rise. Investigating the various degrees of uncertainty in the input parameters and tracking the results of this adjusted model might be good directions for future study. Janková, Zuzana & Dostal, Petr. (2021) [1].

As a result of its rich offshore wind resource, Ireland's renewable generating portfolio includes significant amounts of offshore wind energy. For offshore wind energy projects to be a success, it is crucial to choose the best offshore locations and create energy policy tools that are particular to each location. This study's overarching goal is to identify the most sustainable offshore wind locations in Ireland by creating a multi-criteria decision-making (MCDM) model that takes into account technical, economic, environmental, and social factors. In order to improve outcomes, an interval type-2 fuzzy sets MCDM model is created and used. This model incorporates the score function along with positive and negative solutions. Additionally, in order to make more accurate judgments, modern energy economic measures like the levelized cost of electricity are included into the process. Each of the five potential offshore locations is thoroughly examined in a case study. The outcomes are contrasted with various cutting-edge MCDM techniques. The results show that of the two sites, Arklow Bank-2 is preferable and Sceirde is inferior. Oriel, Dublin Array, and Codling Park are the other locations in the list. The suggested method outperforms its competitors in terms of both stability and ease of implementation. Deveci, *et al*. (2020) [2].

As an environmental component, energy is crucial to human life and growth, and it also plays a significant role in social development. A huge issue has emerged with Turkey's energy usage as a result of the country's fast economic expansion and the dramatic rise in the price of primary energy throughout the globe. To achieve this goal, we employ a fuzzy AHP procedure based on type-2 fuzzy sets to ascertain the decision-makers' views on the relative importance of selection criteria, and we rank the best renewable alternative energy sources using fuzzy multi-criteria decision-making based on the interval type-2 TOPSIS method. Because type-2 fuzzy sets provide extra degrees of independence to reflect the fuzziness and unpredictability of real-world applications, this research proposes a fuzzy multi-criteria decision-making (MCDM) approach to find Turkey's top renewable energy options. Wind emerged as the top choice for Turkey's energy investments, with solar, biomass, geothermal, hydraulic, and hydrogen following closely behind. Three energy planning specialists evaluated each energy option using the 10 criteria we established, and their rankings formed the basis of the final report. Balin, Abit *et al*. (2015) [3].

In multi-criteria decision-making (MCDM), several, often competing, factors are considered before a final choice is made. When solving a problem with ambiguous or missing information, fuzzy decision-making comes in handy. A common issue that academics often address in the literature is fuzzy multicriteria decision-making. We categorize fuzzy multicriteria decision-making techniques into two groups: fuzzy Mult attribute decision-making (MADM) and fuzzy Mult objective decision-making (MODM). In this study, we also examine the current state of these approaches. Since there are several conventional Mult attribute decision-making approaches in the literature, most of the study’s focus on fuzzy MADM. Each approach is accompanied by both tabular and graphical representations. Kahraman, Cengiz et.al. (2015) [4].

Picking services that meet the user's functional and non-functional needs is what's known as service selection. Both on-premises and cloud-based services are available. Using Multi-Criteria Decision-Making Methods, researchers looked at a plethora of service selection evaluations that relied on various services' Quality of Service (QoS) characteristics. Despite its useful results, previous studies have shown that Multi-Criteria Decision-Making Methods cannot address the human-induced fuzziness, incompleteness, ambiguity, and uncertainty that are intrinsic to decision-making processes. Fuzzy multi-criteria decision-making methods are becoming more popular as a means to get around these limitations. Aazagreyir. (2022) [5].

Application To Fuzzy Decision-Making Approach

Fuzzifications of the conventional wisdom about decision-making have long been the norm for fuzzy set applications in this domain. Probabilistic choice theories and game speculations have shown decision-making in dangerous conditions. Because people aren't always clear when they describe their preferences, constraints, and goals, fuzzy decision theories try to account for this. In this analysis, I have described the main types of decision-making situations and how fuzzy set hypothesis may be used to them. Typically, classical decision-making handles a number of observables, subjective conditions (outcomes), a number of observables, subjective activities that the decision maker can choose from, a connection illustrating the state or outcome that is typical of each activity, and finally, a utility or goal function that sorts the outcomes according to their attractiveness.

When the outcomes of any endeavor are clearly defined and attainable, only then should a choice be taken. In this case, we choose the option that leads to the outcome with the most utility. So, increasing the utility capacity becomes an improvement problem rather than a decision-making one. Under risky conditions, or when their contingent probability appropriations, one for each action, are the only available free knowledge about the outcomes, a choice is taken. Here, the decision-making issue shifts to one of optimizing for predicted utility maximization. Decisions are made in an uncertain or vulnerable environment when the outcomes' probabilities are unknown or may not be significant, and when the results for each action are only shown in a crude form. The primary categorization of dynamic problems may be decision-making in the face of vulnerability or uncertainty, as depicted by the British economist Shackle in 1961. Here is where fuzzy decision-making really shines. Typically, people only notice a handful of types of decision-making issues. According to one paradigm, decision problems may be categorized into two types: those with a single chief and those with several decision makers. One group deal with decisions made by an individual, while the other deals with decisions made by a group of people.

An alternative metric acknowledges that there are choice problems, such as optimizing a utility capacity, streamlining according to needs, or improving according to multiple target standards. On the other hand, decisions should be able to be made in a single phase, or at most, they are done in many iterative stages. A fluffy rationale-based control framework may essentially replace any other control framework. While this may be a needless abundance in certain places, it does help organize a lot of disorganized instances. Fluffy logic isn't the answer to every problem, but it can help when applied appropriately. It is not necessary to use a fluffy regulator if a transparent closed circle or PID controller is sufficient. When the prospect of adjusting a PID regulator or setting up a control framework for a complex system seems insurmountable, fluffy framework steps in to help. Sendai, Japan's Sendai Subway framework is widely considered to be one of the best examples of fluffy logic in use.

Multi Criteria Decision Making (MCDM)

An increasing number of scholars are devoting their time and energy to the field of multi-criteria decision-making (MCDM) in the hopes of discovering better ways to make decisions. Alternatives, criteria, and practical ways of obtaining answers are all part of the complex process known as Multi Attribute Decision Making (MCDM), sometimes known as MADM. Finding a perfect solution that meets all the requirements to a large degree is the fundamental goal of every decision-making challenge. Part of decision theory is the reasoning behind multi-criteria decision-making. MCDM is also known as MCDA, with the latter putting an emphasis on analysis. Creating a main decision-making matrix containing criteria and options is the first step in solving an MCDM challenge. Here, choices denote the alternatives, criteria denote the defining characteristics, and the value of the matrix denotes the amount to which the alternatives satisfy the requirements. Despite the abundance of MCDM techniques available today, there are commonalities in the stages used to arrive at the best possible solutions to decision-making challenges.

- Formulation of Decision-Making Matrix
- The following form is used to frame a decision matrix with a limited number of choices and criteria:

$$\text{DM (T)} = \begin{pmatrix} t_{11} & t_{12} & \dots. & \dots. & t_{1j} \\ t_{21} & t_{22} & \dots. & \dots. & t_{2j} \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ t_{i1} & t_{i2} & \dots & \dots & t_{ij} \end{pmatrix}; \text{ i=1,2…m , j=1,2…n}$$

- The above matrix has m alternatives and n criteria where the values of m and n ranges from 1 to I and 1to j respectively
- Computing the Criterion Weights Wj

In some instances, the criteria weights are presumed to be equal, whereas in others, they are calculated taking into account preferences and relative significance.

Normalization of the Matrix

This is a crucial part of making any kind of choice. We normalize and scale the values of the decision matrix down to the range of 0 to 1 since their ranges are different. Various normalizing techniques are used, including linear sum, linear max-min, linear max, and VIKOR.

Finding the Weighted Normalized Matrix

A weighted normalized matrix is produced by multiplying the normalized matrix with the criterion weight vector.

Ranking of the Alternatives Based on the Relative Score Values

After the score values of the options have been computed, they are ranked. The methodologies vary in the mode of computing the score values. Here are the classifiers that the MCDM approaches are built on:

1. Number of decision makers
2. Number of alternatives
3. Nature of the criteria
4. Nature of the values in the decision-making matrix
5. Goals of the decision-making problem
6. Criterion weights computation
7. Calculation of the score values of the alternatives
8. Nature of the decision-making environment

Figure.1. shows the proposed branching of the MCDM based on the aforementioned classifiers.

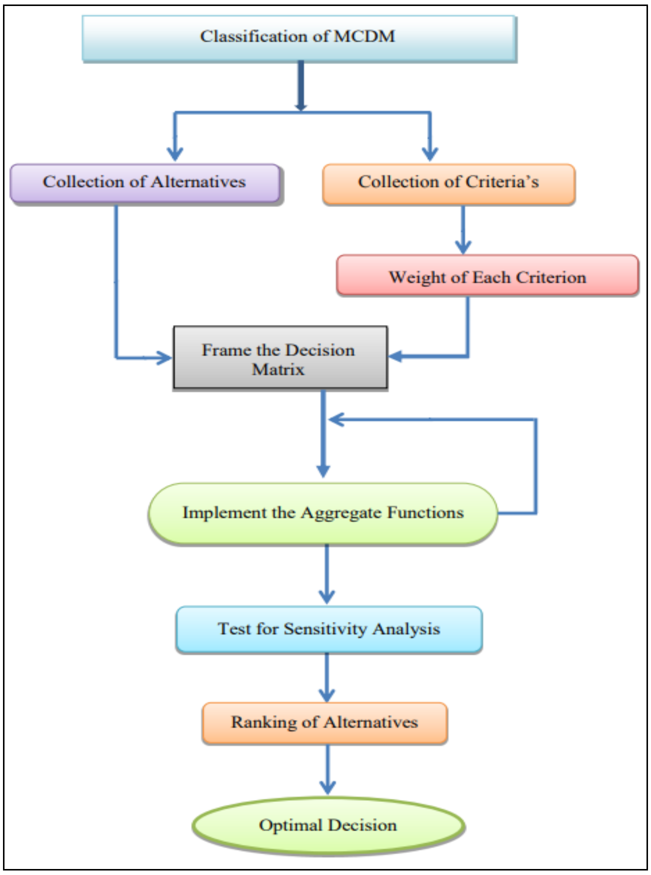

Fig 1: MCDM Framework

Diffusion of Fuzzy Sets into Multicriteria Decision Making

In some cases, the lack of a clear description makes it look like mathematical modeling isn't the best fit for the underlying complexity of the actual choice issue. So, it's possible that the decision-making scenario including fuzzy and crisp data will not satisfy the optimal requirement for a traditional MADM dilemma. For the most part, when there aren't clear limits to the set of observations that the description pertains to, the word "fuzzy" usually denotes a circumstance where the aim or characteristic cannot be specified precisely. In a similar vein, there are cases when there is insufficient data to make an informed decision or if the crisp value is insufficient to accurately represent actual circumstances. Regrettably, traditional MADM approaches are ill-suited to challenges like these since they presume that all criterion performances are known and can be expressed numerically.

For MADM tasks when precise definitions or evaluations of success are lacking, fuzzy set theory provides a useful framework. Adding fuzziness or imprecision to a MADM dilemma will unavoidably make the choice situation more difficult in numerous ways. When looking for the best options, sorting fuzzy or qualitative data is more computationally intensive since it is operationally more complex to modify than crisp data. For issues that were previously intractable and unsolvable using conventional MCDM approaches, they paved the way for a new class of methodologies. Making decisions in a hazy setting: the first strategy. One of their suggestions was to define fuzzy goals and fuzzy constraints as fuzzy sets in the space of options. Then, the choice could be made as the point where the constraints and goals were converging. Then, we said that a maximizing choice was a spot in the universe of possible alternatives where a fuzzy decision's membership function was at its maximum.

The two stages of MADM-criteria rating and multiple aspect alternative ranking utilizing fuzzy sets-formed their strategy. An all-fuzzy decision set is the intersection of all fuzzy objectives. When faced with a decision-making dilemma involving many attributes, the ideal solution should have the greatest membership values across all criteria. However, in practice, this is seldom the case. By combining the max and min operators, he proposed a compromise method that would allow us to reach the most acceptable choice. In order to find out how important each quality is, he recommended using the Saaty approach, which involves comparing two things using the reciprocal matrix. The uses of fuzzy set theory in MADM issues were outlined by Kickert (1978). MADM is used in two works by Zimmermann (1985, 1987). Numerous high-quality surveys of fuzzy MCDM are available.

The fuzzy sets and multi criteria decision making

Managing the uncertainty of human cognition is made possible by the third dimension. When dealing with ambiguity, type-2 fuzzy sets perform better than type-1 fuzzy sets. When dealing with decision-making issues, type-2 fuzzy sets provide more sensitive solutions. A single element's membership may take on several values using HFS, which was first proposed by Torra. By allowing the use of all conceivable membership values acquired from a group of experts, HFS are seen as an extension of ordinary fuzzy sets. As a result, HFS may be helpful for decision makers who are hesitant to express their opinions. Atanassov created Intuitionistic Fuzzy Sets (IFS) as a way to reflect uncertainty in decision-making caused by decision makers' reluctance. IFS are generalizations of fuzzy sets. When dealing with decision-making data that is either too vague or too imprecise, an IFS—which is distinguished from conventional fuzzy sets by its membership and non-membership functions-is considered to be a helpful tool.

For decision-making issues, fuzzy sets in the space of alternatives properly describe fuzzy limits and fuzzy objectives. Its highlighted significance has decision-makers desiring to approach issues of energy policy making with more sensitivity. When it comes to issues with energy policy and decision-making, fuzzy logic is seen as an appropriate method for obtaining more sensitive findings. Hence, decision makers augment traditional MCDM approaches with various fuzzy sets, including type-1 and type-2 fuzzy sets, HFS, and IFS. Improved realism in decision-making is possible with fuzzy MCDM approaches. Fuzzy sets are often utilized with Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), AND TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) algorithms. Conversely, methods such as fuzzy Axiomatic Design (AD), fuzzy Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), fuzzy Multicriteria Optimization and Compromise Solution (VIKOR), and fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) are used to find more sensitive solutions. Furthermore, energy issues often include the use of integrated fuzzy decision-making models, which incorporate many fuzzy MCDM methodologies. Figure 2. shows that there are several ways to categorize fuzzy MCDM systems, including those based on distance, outranking, pairwise comparison, and others.

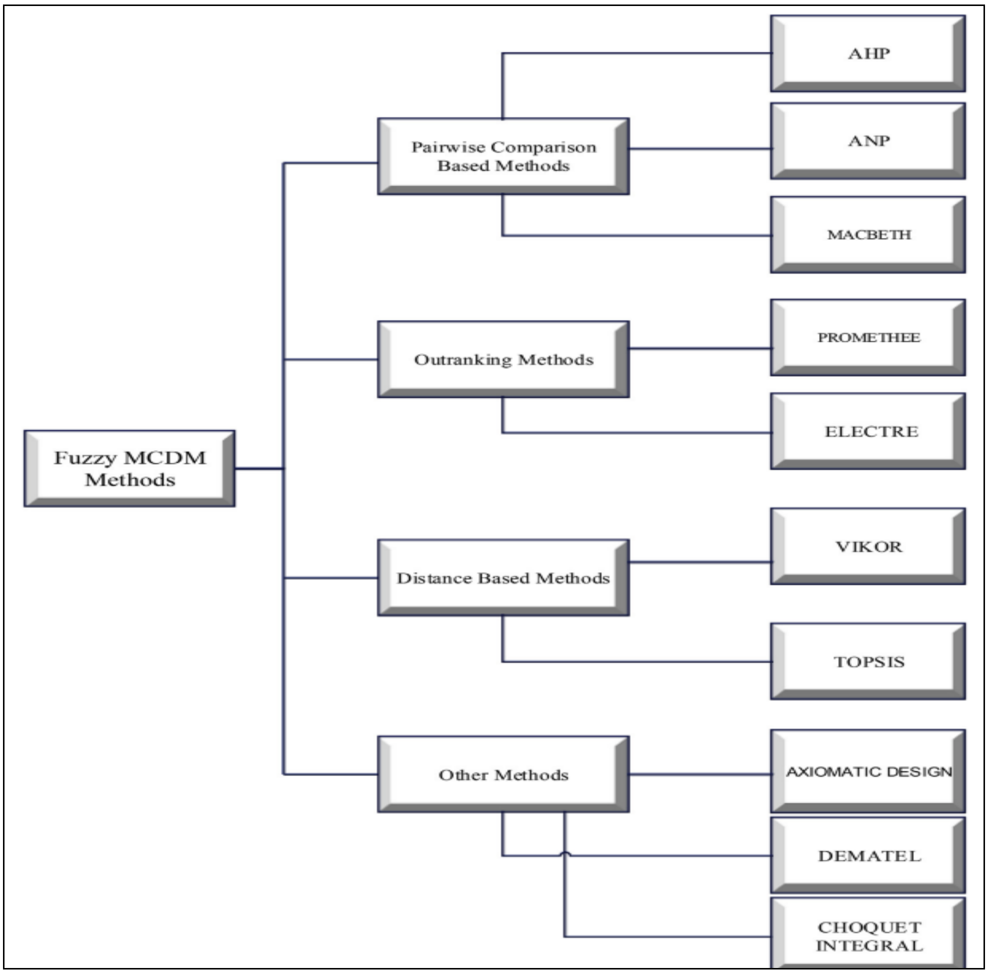

Fig 2: A classification of fuzzy MCDM methods

Conclusion

Multi-Criteria Decision Making (MCDM) provides a strong foundation for handling the complexity of decision-making in subjective and ambiguous situations by using fuzzy set theory. Fuzzy Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) are two methods that researchers can use to improve decision-making. These methods allow them to systematically evaluate alternatives, give enough weight to criteria, and synthesize performance feedback. Understanding human cognition and preferences on a more sophisticated level is made possible by fuzzy logic's ability to handle ambiguity and imprecision. Fuzzy logic has come a long way, and new developments like neutrosophic sets, intuitionistic fuzzy sets, and type-2 fuzzy sets allow for the incorporation of higher-order uncertainties like hesitation and indeterminacy, considerably enhancing analytical capacities. This comprehensive method promotes fair decision-making while also increasing the precision of evaluations. When MCDM techniques are used, the symmetry checks that are built in help to reduce bias and make sure that different criteria are being evaluated fairly and openly. As

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