Analysis of trends and applications of Multi-Criteria Decision-Making methods

ABSTRACT

Multi-Criteria Decision-Making (MCDM) methods provide effective tools for evaluating, comparing, and ranking alternatives based on multiple criteria, thereby assisting decision-makers in making rational and well-founded choices. This study aims to categorize MCDM methods and explore the practical contexts in which they are applied by mining data from the keywords and abstracts of 14,089 scientific research articles in the Scopus database using text mining techniques. In the recent years, MCDM research has grown significantly, driven by contributions from Asia and Europe and spanning diverse fields like computer science, engineering, mathematics. Supported by substantial funding, these studies highlight MCDM's broad applicability and enduring impact on decision-making. The analysis reveals the diversity of methods such as Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS), and fuzzy variantsare identified as central methods with application contexts ranging from ranging from supply chain management and performance evaluation to energy and environmental management, among others. Moreover, sensitivity analysis is frequently applied due to its critical role in enhancing the reliability of MCDM methods, ensuring that small changes in input parameters do not significantly impact the final decision outcomes. Additional findings, including specific applications and methodological trends, will be further discussed in the discussion section. These findings provide a comprehensive overview of the prevalence and usage trends of MCDM methods, while also highlighting research gaps and potential future applications.

Keywords: *MCDM, systematic review, text mining.*

1. INTRODUCTION

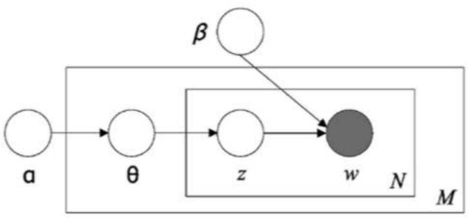
Humans constantly make decisions, and decision-making is inherently complex and challenging. MCDM methods represent a crucial field in research and practice, addressing complex decision-making problems where multiple criteria must be considered simultaneously. MCDM assists decision-makers in ranking or selecting the best alternatives based on numerous, often conflicting, criteria. MCDM can be considered both old and new; old because it dates back to the 1700s, and new because the group of MCDM methods has continuously evolved over time.[1] During its development process, to enhance decision-making capabilities under uncertainty, one of the significant advancements in this field is the development of fuzzy multi-criteria decision-making (F-MCDM), which incorporates fuzzy logic to handle ambiguity and imprecision in criteria evaluation.[2,3] In decision-making problems, fuzzy goals and constraints are represented as fuzzy sets within the space of alternatives, making fuzzy logic particularly adept at addressing complex decision-making issues, especially in scenarios where conventional methods may prove inadequate. While MCDM methods are widely applied across various domains, selecting the most suitable MCDM method for a specific problem remains a significant challenge. The diversity of Fuzzy MCDM (FMCDM) methods, each with unique assumptions and operational mechanisms, implies that no single method can be deemed 'universal'. For example, the Fuzzy Analytic Hierarchy Process (FAHP) is effective for pairwise comparisons of criteria but struggles with large-scale problems. In contrast, the Fuzzy Technique for Order Preference by Similarity to the Ideal Solution (Fuzzy-TOPSIS) is more appropriate for problems that involve evaluation based on proximity to an ideal solution. To address complex problems more effectively, MCDM methods are also often combined into integrated models. Vincke categorizes MCDM methods into three main components: multiple attribute utility theory, outranking methods, and interactive methods.[4] However, a more algorithmic approach groups these methods into distance-based, outranking, and pairwise comparison methods.[5] BaydaS et al. argue that the algorithms of different MCDM methods do not always yield the same optimal solution or hierarchical ranking, highlighting a critical issue in the absence of a standardized evaluation framework for comparing MCDM methods.[6] The urgency of this need is underscored by our refined research focus on utilizing MCDM. Previous literature reviews have attempted to address this issue. For instance, Kaya et al. reviewed 245 papers published between 2000 and 2017, analyzing FMCDM methods in the context of energy policy-making,[5] the study found that the FAHP, either as a standalone tool or integrated with other MCDM methods, was the most commonly used, and Type-1 fuzzy sets were the most preferred type of fuzzy sets. Both single and integrated MCDM methods have been extensively used in the field of corporate sustainability, with single MCDM methods showing a dominant presence.[6,7] In the context of medical decision-making, particularly during the COVID-19 pandemic, the use of MCDM methods has been critical in optimizing treatment processes and resource management. Notably, methods such as AHP, TOPSIS, and PROMETHEE (Preference Ranking Organization Method For Enrichment Evaluation) have proven highly beneficial in supporting decision-making under the urgent circumstances of the pandemic.[8] These findings are consistent with research that highlights the prominence of AHP and TOPSIS in healthcare settings.[9] In addition, VIKOR, AHP, ANP, PROMETHEE, and hybrid methods have been widely employed in studies focusing on low-carbon transport and green logistics, showcasing the versatility and adaptability of MCDM approaches in sustainable development.[10] To address the research gap, this study consolidates all previously published studies available in the Scopus database up until 9:30 AM on September 19, 2024 (GMT+7). By doing so, it aims to provide a comprehensive overview of the application trends of MCDM methods across various fields.

2. METHODOLOGY

2.1. Methodology

This study employs text mining techniques for knowledge discovery through Python programming, a reliable and technology-driven approach that effectively extracts insights from large datasets.[11,12] Compared to other text mining tools such as Gephi or VoSViewer, Python programming allows us to fully understand and control the underlying algorithms, offering the advantage of customizing functions without the limitations commonly encountered with pre-built software.

We employed statistical descriptive analysis techniques and co-occurrence analysis, supplemented by Latent Dirichlet Allocation (LDA). LDA, a widely used method in machine learning and text mining, is an unsupervised statistical model that identifies hidden topics within a collection of textual documents without human intervention. Recent studies have demonstrated the effectiveness of LDA in uncovering latent topics in various research contexts.[13,14] In the visual representation shown in Figure 1, rectangles are used as iterative markers, where 'M' denotes documents, and 'N' represents the frequency of topics within those documents. Observable words, indicated as 'w' are derived from the topic distribution 'z'. In this framework, 'β' signifies the word distribution across topics, 'θ' describes the distribution of topics over documents, and 'α' indicates the word distribution within specific topics. LDA analysis was performed on all abstracts using multiple Python libraries, with PyLDAvis utilized to assess the mean separation between topics.



$$p(\theta, z, w \mid \alpha, \beta) = p(\theta \mid \alpha) \prod_{n=1}^{N} p(z_n \mid \theta) p(w_n \mid z_n, \beta)$$

Figure 1. Latent Dirichlet Allocation model[14].

2.2. Dataset

The data source for this study consists of keywords and abstracts extracted from final articles and conference papers indexed in Scopus to ensure a certain level of reliability. The search syntax used is as follows:

(TITLE-ABS-KEY (mcdm) OR TITLE (multiple-criteria AND decision AND making)) AND (LIMIT-TO (DOCTYPE , 'cp') OR LIMIT-TO (DOCTYPE , 'ar')) AND (LIMIT-TO (LANGUAGE , 'English')) AND (LIMIT-TO (SRCTYPE , 'p') OR LIMIT-TO (SRCTYPE , 'j')) AND (LIMIT-TO (PUBSTAGE , 'final')).

Before analysis, the data was normalized by converting all keywords and methods to lowercase to ensure a more accurate match with the terms in the CSV file. Additionally, numbers, punctuation, and non-essential words (e.g., am, is, are) were removed using the stopwords library, which is believed to streamline and simplify the analysis process. Finally, keywords such as 'decision making', 'decision-making', 'decision makings', and 'mcdm' (which convey similar meanings) were excluded due to their general nature.

3. RESULTS AND DISCUSSION

The recent surge in research on MCDM is notable (Figure 2). The majority of the documents are relatively new, having been published within the last 15 years. In 2003, only 41 studies related to MCDM were recorded. By 2013, this number had increased nearly ninefold to 369 publications, accounting for approximately 18.8% of the total 1,964 publications recorded by the end of 2023, with a continued upward trend expected into 2024. MCDM research involves a diverse group of authors from various countries. The top five countries contributing the most to the MCDM research landscape are India, China, Iran, Turkey, and Taiwan. India leads with 3,006 publications, accounting for approximately 21.3% of the total research output in this domain. China follows closely with 2,084 publications, representing about 14.8%, while Iran contributes 1,495 documents (10.6%). Turkey and Taiwan add 1,459 (10.4%) and 1,120 (8%) publications, respectively. These five countries together account for more than 65% of the global research on MCDM, highlighting their dominant role in advancing this field. MCDM is indeed a major area of interest in China, as the top three funding organizations in this field are the National Natural Science Foundation of China, the Ministry of Science and Technology of the People's Republic of China, and the Fundamental Research Funds for the Central Universities. However, leading the field in MCDM research, as of the data extraction from the Scopus database, is Edmundas Kazimieras Zavadskas from Lithuania's Vilnius Gediminas Technical University, contributing to the university's top position in publication productivity within the MCDM field. With an H-index of 106, he has authored 200 studies related to this domain, establishing himself as a prominent contributor to the advancement of MCDM methodologies.

Figure 3-Data analysis reveals that MCDM research is most prevalent in the fields of

Computer Science (5,817 documents), Engineering (5,727 documents), Mathematics (3,050 documents), Business, Management and Accounting (2360 documents) highlighting the methods' widespread application in addressing technical problems, optimization, and mathematical modeling. Significant research activity is also observed in Business, Management, and Accounting (2,427 documents), Environmental Science (2,265 documents), and Energy (1,602 documents), underscoring the importance of MCDM in performance evaluation and sustainable decision-making within these domains. In contrast, fields such as Nursing (15 documents), Dentistry (5 documents), and Veterinary (5 documents) show limited MCDM research, indicating untapped potential in these areas.

To provide an overview of key methodologies in MCDM, this study highlights the three most-cited works in the field. At the time of data extraction, the three most-cited works in the field of MCDM highlight the diversity and evolution of methodologies. The study '*Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS*' (3639 citations) compares the effectiveness of VIKOR in generating compromise solutions and TOPSIS in ranking alternatives.[15] The paper '*Extensions of the TOPSIS for group decision-making under fuzzy environment*' (3088 citations) introduces novel enhancements to the TOPSIS method, making it suitable for group decisions in uncertain contexts.[16] Lastly, '*Best-worst multi-criteria decision-making method*' (2863 citations) proposes an innovative MCDM approach that offers simplicity and effectiveness in weight derivation and ranking processes.[17] These studies have significantly influenced both theoretical and practical advancements in MCDM.

MCDM has become a crucial tool in various research fields and practical applications. From the keyword frequency chart (Figure 4), it is evident that the TOPSIS, AHP and Fuzzy sets are the most widely used methods, extensively applied in research related to supplier selection, optimization, and decision support systems. These methods facilitate the evaluation and ranking of alternatives based on multiple criteria, aiding decision-makers in selecting the most optimal option. Additionally, methods such as Entropy, VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje), and TOPSIS are also employed to address complex issues in areas such as sustainable development and risk management. In MCDM, the outcomes are often influenced by the weights and input values of the criteria. Sensitivity analysis examines whether small changes in the weights or input values significantly alter the rankings or final results. This ensures that decisions based on MCDM are reliable. Sensitivity analysis is a widely used and popular tool in MCDM research, as evidenced by the findings of our study (Figure 4). Assessments also indicate that Decision Support Systems (DSS) and Geographic Information Systems (GIS) are essential complementary tools for MCDM, enhancing its applicability in complex domains. DSS focuses on providing comprehensive support throughout the decision-making process, while GIS delivers detailed spatial data and analysis. Their integration creates robust, efficient, and practical solutions for addressing multi-criteria decision-making problems.

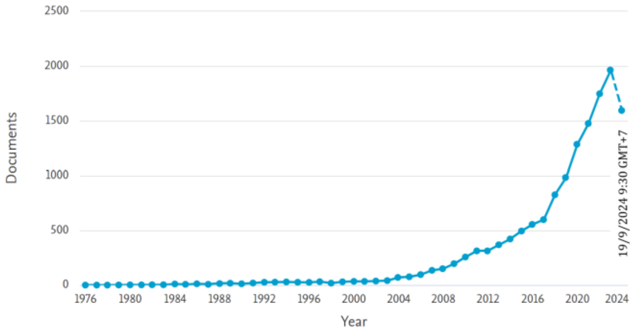


Figure 2. Documents by years (Source: Scopus).

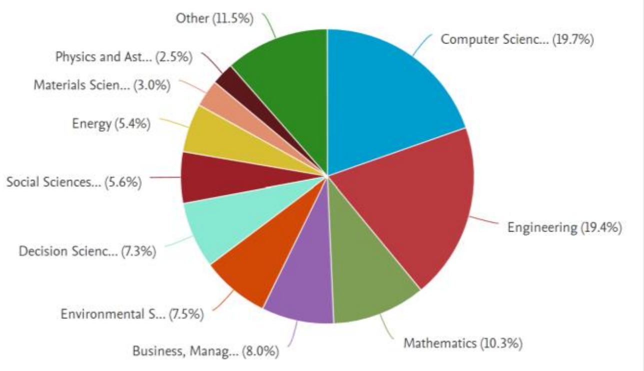


Figure 3. Documents by areas (Source: Scopus).

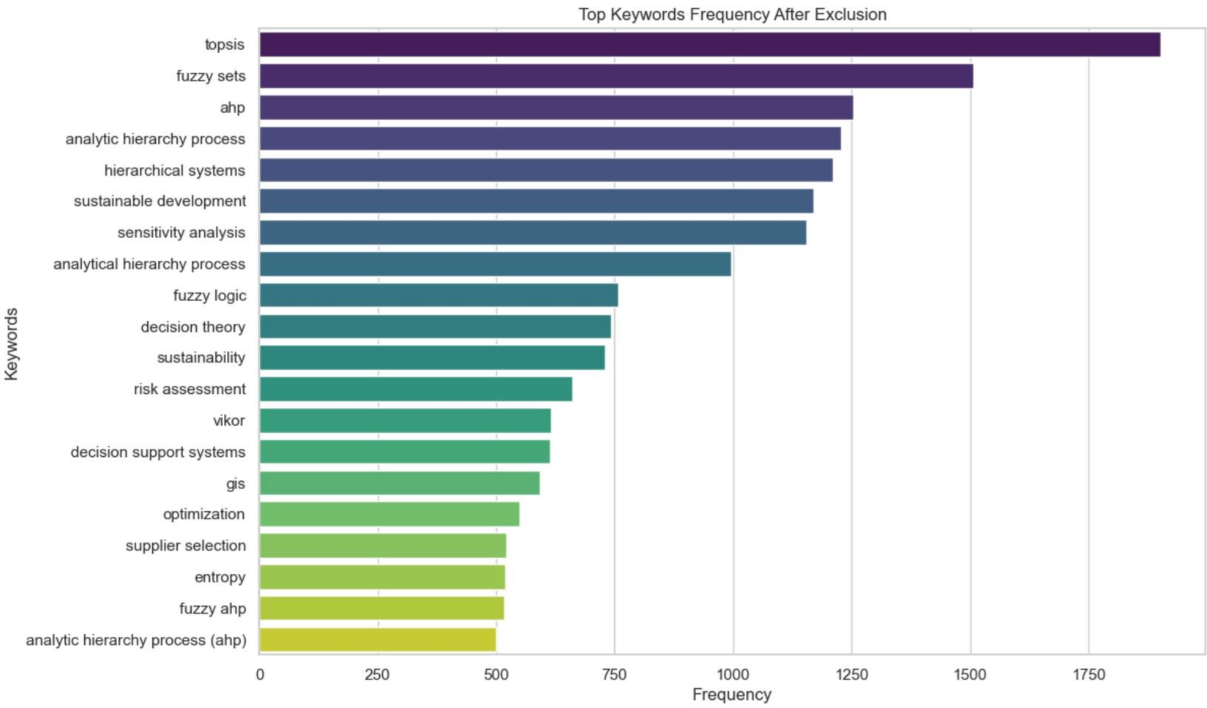


Figure 4. Top keywords frequency after exclusion.

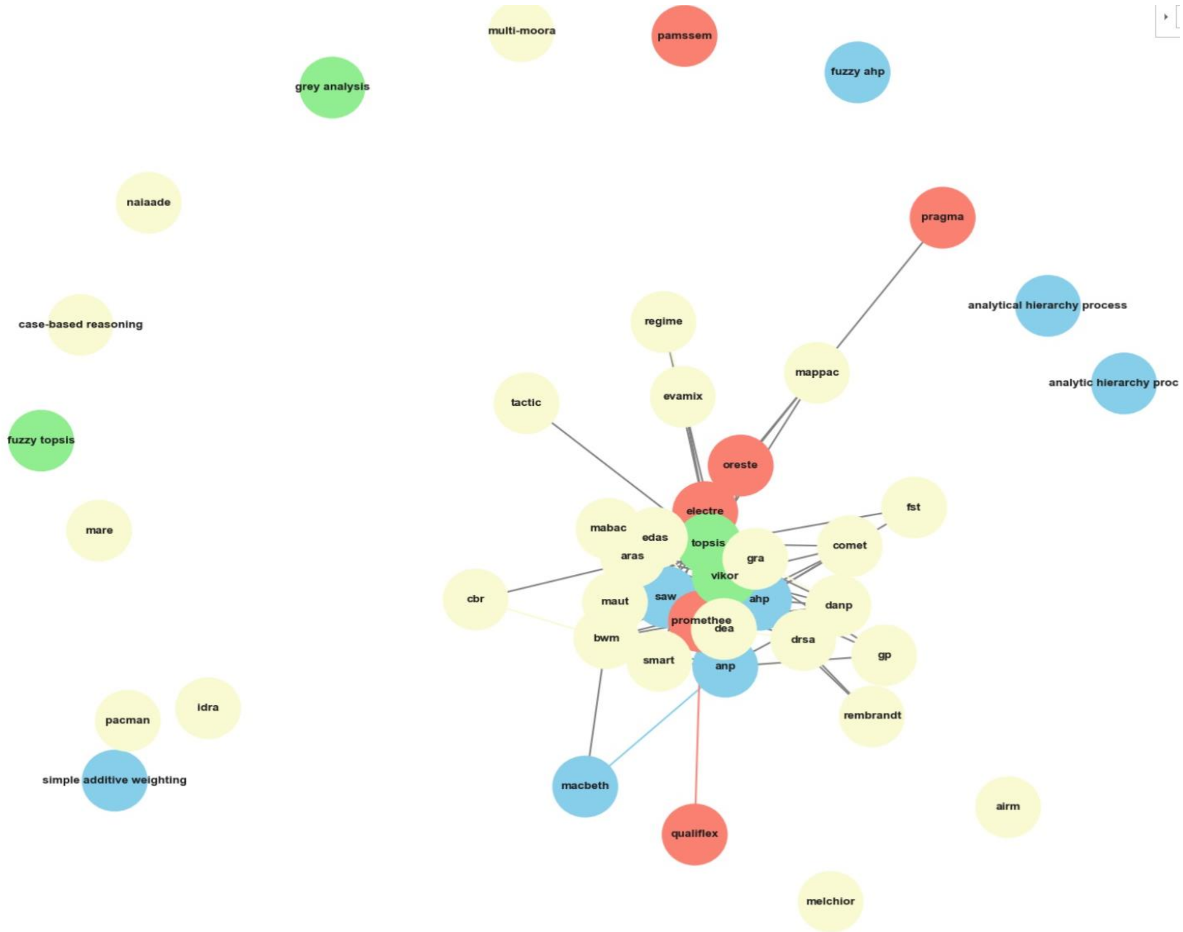


Figure 5. Co-occurrence Network of MCDM.

In this study, we applied topic analysis using the Latent Dirichlet Allocation (LDA) model to explore the main themes within abstracts related to MCDM. The LDA model is an unsupervised machine learning technique commonly used for text analysis, designed to uncover latent topics based on the distribution of keywords within the documents.

- Topic #1: 0.013* “criteria” + 0.011* “study” + 0.008* “selection” + 0.008*"method" + 0.007* “supply” + 0.006* “process” + 0.006* “used” + 0.006* “supplier” + 0.006* “service” .
- Topic #2: 0.032* “fuzzy" + 0.023* “method" + 0.016* “proposed” + 0.015* “criteria” + 0.015* “decision” + 0.009* “based” + 0.009* “paper” + 0.009* “alternatives” + 0.008* “approach” .
- Topic #3: 0.015* “energy” + 0.009* “study” + 0.007* “using” + 0.007* “water” + 0.006* “power” + 0.006* “results” + 0.006* “used” + 0.006* “analysis” + 0.005* “environmental” .
- Topic #4: 0.011* “model” + 0.010* “criteria” + 0.009* “decision” + 0.009* “study” + 0.008* “process” + 0.007* “performance” + 0.007* “evaluation” + 0.006* “research” + 0.006* “factors” .

The indicators and keyword weights within each topic provide valuable insights into the research trends and applications of MCDM methods across various fields.

- Methods for criteria selection and evaluation in supply chain and services:

Topic 1 from the LDA analysis highlights the prevalence of keywords such as ‘criteria’ ‘selection’, and ‘supplier’, suggesting the significant role of MCDM methods in selection and evaluation within supply chains. Keywords indicate a focus on identifying and prioritizing decision criteria to optimize supplier selection and service processes. The presence of terms like ‘method’ and ‘study’ reflects a methodological emphasis, highlighting the importance of systematic approaches in these domains. This pattern underscores the relevance of MCDM techniques in addressing complex decision-making challenges in supply chain operations, where selecting the right supplier or service is crucial for overall efficiency and effectiveness.

- Fuzzy methods in decision making:

Topic 2 indicates that fuzzy methods such as Fuzzy AHP, Fuzzy TOPSIS, and other variants play a crucial role in tackling decision-making problems under uncertainty or when dealing with hard-to-quantify information. The use of fuzzy methods allows for the integration of complex and ambiguous criteria into the decision-making process, leading to more accurate and relevant outcomes. This is particularly important in fields requiring the handling of incomplete or highly variable data. The analysis results show that the widespread use of fuzzy methods in research underscores the importance of combining qualitative and quantitative factors in decision-making.

- Evaluation methods in energy and environmental issues:

Topic 3 underscores the application of MCDM methods in the fields of energy and the environment, with keywords related to ‘energy’, ‘water’, and ‘environmental’. Words such as ‘analysis’ and ‘results’ indicate an emphasis on using systematic methodologies to derive actionable insights. The presence of these methods in research indicates the growing trend of applying MCDM to address global issues related to environmental protection and efficient resource use.

- Performance evaluation and decision-making models:

Topic 4 highlights a distinct focus on decision-making models and performance evaluation. This theme leans toward the conceptual and methodological underpinnings of decision-making processes. It emphasizes the interplay between decision criteria, performance metrics, and influencing factors, reflecting research aimed at refining the theoretical frameworks and evaluation tools used in diverse decision-making contexts. This orientation suggests a broad applicability of the discussed models, extending beyond domain-specific uses to encompass a wide range of industries and scenarios, making it a foundational area in MCDM studies.

Transitioning to the co-occurrence network of MCDM (Figure 5), the visualization reveals key relationships between frequently occurring keywords, offering insights into how different methods and applications are interconnected. In the visualization (Figure 5), nodes are color-coded to represent different groups of methods. For instance, methods within the 'Pairwise comparison' group might be represented by one color, while methods in the 'Outranking' group could be shown in a different color. The lines connecting the nodes indicate the co-occurrence of methods within the same summary. The proximity of nodes may reveal the degree of relatedness between methods; nodes that are closer together might appear together more frequently.

In the field of MCDM, methods are often categorized into various groups based on their approaches. The 'Pairwise comparison' group includes methods such as the AHP, ANP, and SAW (Simple Additive Weighting), plays a crucial role in evaluating criteria through pairwise comparisons between factors. AHP is particularly noted for its capability to handle complex issues, hierarchical goal settings, and criteria comparisons based on weights, especially when combined with fuzzy methods to better manage uncertainty. This finding aligns with the previous research by Kaya et al. also concluded that AHP, ANP, and TOPSIS (other group) methods, while widely applied in various contexts, are particularly prevalent in the field of energy policy-making when used in conjunction with fuzzy sets. Other study suggests that Fuzzy TOPSIS is more effective when the values may vary or when there is vagueness.[18] Although ANP is advantageous in complex decision-making scenarios, it heavily relies on human judgment. An expert in the field can significantly enhance the results, whereas a novice may adversely affect the outcomes.
The 'Outranking' group focuses on evaluating and ranking options by comparing their advantages and disadvantages, with prominent methods such as PROMETHEE and ELECTRE . These methods are widely applied in decision-making situations involving conflicting criteria, helping to identify superior options by eliminating weaker alternatives. According to Kaya et al., the popularity of fuzzy ANP, fuzzy ELECTRE, and fuzzy PROMETHEE in the field of energy policy-making is quite similar.[5] However, these two methods may not necessarily be prevalent in many other scenarios. The authors note that despite their potential, ELECTRE and PROMETHEE have not been widely applied in sustainability assessments in urban settings, with limited research utilizing these methods in this particular area.[19] However, these methods hold promising potential for the future, as there has been considerable interest in improving them, leading to the development of various versions such as ELECTRE I, II, III, and IV, as well as PROMETHEE I, II, and III. The presence of ORESTE alongside ELECTRE and PROMETHEE underscores the prominence of outranking methods in MCDM. The positioning of ORESTE (Organization, Rangement Et Synthèse De Données Relationnelles) near these established methods highlights its role as an alternative in scenarios requiring outranking techniques. Unlike methods such as ELECTRE or PROMETHEE, which are often preferred for their ability to handle numerical data and more detailed preference structures, ORESTE is particularly well-suited to situations where qualitative assessments or ordinal rankings of alternatives are essential. This distinction suggests that ORESTE is not commonly integrated with ELECTRE or PROMETHEE but rather provides a substitute for decision-making contexts with incomplete information or less quantifiable criteria.[20] Such a comparison underscores the diversity within the outranking family, allowing practitioners to select the most appropriate method for their specific decision-making challenges.

The analysis results reveal the diversity and widespread application of MCDM methods in both research and practical applications, underscoring their importance in supporting effective and accurate decision-making. Evidence suggests that methods like VIKOR are also employed to address complex issues in risks fields within supply chain. Notably, VIKOR and TOPSIS, both belonging to the distance-based group, are widely applied in supply chain planning.[21]

Based on the analysis of the diagram, the yellow-labeled methods (such as MABAC (Multi-Attributive Border Approximation area Comparison), CBR (Criteria-based ranking), MAUT (Implementation of Multi-Attribute Utility Theory), SMART (The Simple Multi Attribute Rating Technique), etc.) are scattered around the central cluster where other methods (such as AHP, ANP, TOPSIS, PROMETHEE) are concentrated. This suggests that these methods play a complementary role and are often combined with other groups of methods to address complex problems. Specifically, their distribution indicates that distance-based methods are not only used independently but are also integrated with methods from the pairwise comparison group (such as AHP, ANP) or the outranking group (such as PROMETHEE, ELECTRE) to leverage the strengths of each and enhance the accuracy of analyses.

The positioning of the yellow-labeled methods around the central cluster signifies that, while they may not serve as primary tools, they are indispensable in supporting multi-criteria decision-making processes. This highlights the importance of integrated approaches in MCDM research, where the combination of methods creates multidimensional analytical models, particularly in fields such as supply chain planning, risk management, and performance evaluation.

4. CONCLUSION

Research in the field of MCDM has experienced a significant surge over the past 15 years, with a noticeable concentration of contributions from Asian authors and European experts. This growth reflects the increasing recognition of MCDM as a critical tool in addressing complex decision-making challenges across diverse domains. The research field itself is highly diverse, with disciplines such as engineering, computer science, and mathematics collectively accounting for nearly 50% of the total studies. Furthermore, the field has attracted substantial funding from various sources, with Chinese funding agencies, standing out as prominent contributors to advancing research and project implementation. Notably, studies with high citation indices highlight the practical and theoretical significance of MCDM methods, underscoring their broad applicability and enduring impact on both academic and professional practices.

Suprisingly, BWM has been established as a pivotal reference for future research due to its introduction or enhancement of a critical aspect. Nevertheless, the limited practical application or adoption of BWM in other studies could explain its rare appearance in keywords. This observation suggests that despite BWM's high academic value, researchers might favor other methods in MCDM due to their greater applicability or familiarity. Numerous methods have been identified and extensively utilized across various domains, reflecting the diversity and adaptability of MCDM approaches. The analysis highlights the prevalence of key methodological groups, such as pairwise comparison, distance-based, and outranking methods, each catering to distinct decision-making contexts. Among these, methods like AHP, TOPSIS, and their fuzzy variants emerge as the focal points of research, dominating studies in fields such as supply chain management, energy policy-making, and sustainability assessments. These methods are frequently integrated with other approaches to enhance decision-making precision and address multidimensional challenges. The integration of these method groups has proven particularly effective in leveraging their complementary strengths, providing more robust and nuanced analyses. These findings underscore the ongoing evolution of MCDM methodologies and their critical role in tackling complex decision-making scenarios.

Looking forward, studies should further explore advanced sensitivity analysis techniques and their integration with evolving MCDM frameworks to address increasingly complex decision-making challenges.

While listing and analyzing MCDM methods can provide an overview, there is often a lack of in-depth analysis regarding the effectiveness and limitations of each method within specific contexts. This can diminish the practical value and specificity needed for subsequent research. To address gaps, future studies could also explore dynamic topic models that extend LDA to incorporate temporal changes, enabling better forecasting of research directions. Integrating LDA with semantic embedding techniques like word2vec or BERT could also capture richer contextual relationships, enhancing topic interpretability. These improvements would make LDA-based approaches more robust and better suited for predictive applications in MCDM research.

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