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Review

Integrating Multi-Criteria Decision-Making Methods with Sustainable Engineering: A Comprehensive Review of Current Practices

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Abstract: Multi-criteria decision-making (MCDM) methods have gained increased attention in sustainable engineering, where complex decision-making problems require consideration of multiple criteria and stakeholder perspectives. This review paper provides a comprehensive overview of the different MCDM methods, their applications in sustainable engineering, and their strengths and weaknesses. The paper discusses the concept of sustainable engineering, its principles, and the different areas where MCDM methods have been applied, including energy, manufacturing, transportation, and environmental engineering. Case studies of real-world applications are presented and analyzed, highlighting the main findings and implications for engineering practice. Finally, the challenges and limitations of MCDM methods in sustainable engineering are discussed, and future research directions are proposed. This review contributes to the understanding of the role of MCDM methods in sustainable engineering and provides guidance for researchers and practitioners.

Keywords: sustainable engineering; MCDM; AHP; TOPSIS; fuzzy sets; ANP; DEMATEL; BWM; VIKTOR; GRA; entropy

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1. Introduction

Multi-criteria decision-making (MCDM) methods have become a necessary tool throughout contemporary engineering practice [1]. They enable decision-makers to assess complex problems involving multiple criteria, trade-offs, and uncertainties. The methods used in MCDM are especially beneficial when applied to sustainable engineering, where decision-making requires balancing economic, environmental, and social considerations [2,3].

Sustainable engineering aims to design and implement engineering solutions that are environmentally friendly, socially acceptable, and economically viable [4]. Achieving sustainability requires the consideration of multiple criteria, such as resource conservation, pollution prevention, energy efficiency, economic feasibility, social equity, and stakeholder participation [5–7]. Sustainable engineering challenges decision-makers to balance these criteria and make trade-offs among them to identify the best solutions [8].

MCDM methods can assist in the decision-making process by offering an organized and transparent framework for assessing alternative solutions based on a variety of criteria. These methods enable decision-makers to identify optimal solutions by conducting quantitative and qualitative assessments, taking into account the preferences and priorities of different stakeholders [9].

The purpose of this review paper is to provide a thorough overview of the different MCDM methods and their applications in sustainable engineering. The review explores how MCDM methods could be utilized in various areas of sustainable engineering, including energy, manufacturing, transportation, and environmental engineering. The review also analyzes case studies of real-world applications of MCDM methods and highlights the strengths and weaknesses of each approach.

The motivation for this review is to address the need for a comprehensive and up-to-date overview related to MCDM methods regarding sustainable engineering. The need arises from the increasing importance of sustainability in contemporary engineering practice [1] and the growing complexity of decision-making problems [10]. This review paper seeks to contribute to the existing literature by highlighting the most effective MCDM methods for sustainable engineering problems and by proposing future research directions.

Its primary objectives are:

- To offer a comprehensive overview of different MCDM approaches and how they are used in sustainable engineering;
- To analyze case studies of real-world applications of MCDM methods in sustainable engineering and to highlight their outcomes;
- To identify the strengths and weaknesses of each MCDM technique in sustainable engineering and to compare and contrast them;
- To propose future research directions and discuss how MCDM methods can be further developed to enhance their effectiveness and applicability in sustainable engineering.

This review paper aims to contribute to the ongoing efforts to develop sustainable engineering solutions by providing decision-makers with a framework for selecting the most effective MCDM methods for their specific problems. By doing so, the review paper aims to enhance the effectiveness and applicability of MCDM methods in sustainable engineering and grow what is currently the state-of-the-art in the field.

To achieve the objectives, the review paper is organized in the following manner. After the Introduction, Section 2 is presented. The Primary Results are presented, followed by a presentation of the Detailed Review Results. A summary of the principles and applications of MCDM methods is presented, highlighting their importance and relevance to sustainable engineering. Next, the specific areas of sustainable engineering where MCDM methods have been applied are discussed, and the outcomes achieved are reviewed. Case studies of real-world applications of MCDM methods in sustainable engineering are then presented, and the main findings and implications for engineering practice are analyzed. Following this, the challenges and limitations of MCDM methods in sustainable engineering are then discussed, and prospective research recommendations are proposed. Finally, the main contributions of this review paper are summarized, and the implications for decision-making in sustainable engineering are suggested.

2. Materials and Methods

The knowledge used to conduct this research was obtained from various sources, including published research papers, technical reports, and case studies in academic journals. A thorough search was conducted using the Web of Science (WoS) Core Collection Database, as well as the online EBSCO Discovery Service engine. The search terms used included MCDM, sustainability, and sustainable engineering, with various combinations of these keywords also utilized. The search was limited to papers published between 2018 and 2023, written in English, and focused on MCDM methodologies employed for sustainable engineering.

After an initial screening of search results based on the titles and abstracts, a total of 36,490 articles associated with MCDM methods across different disciplines was identified, with 12,879 of these articles specifically addressing MCDM methods in sustainable engineering.

The case studies presented in this paper were selected based on their relevance and representativeness to the applications of MCDM methodologies in sustainable engineering. The cases were analyzed using a systematic approach to identify the decision-making problems, the criteria used, and the outcomes achieved. The case studies were also used to illustrate the strengths and limitations of various MCDM methods, as well as to identify the challenges and opportunities for future research in this area.

3. Primary Results

The publishers of articles pertaining to the use of MCDM methods across various fields of sustainable engineering are diverse and include well-known names such as Springer Nature, Elsevier, Wiley-Blackwell, and Taylor & Francis Ltd. (Figure 1). However, the publisher with the most articles published in this field is MDPI, with 4264 articles. Other publishers with a significant number of articles include Hindawi Limited, Emerald Publishing Limited, and IOS Press. The list also includes smaller publishers such as the Rural Outreach Program and Dr. M.N. Khan, indicating a wide range of contributors to this field. The diversity of publishers reflects the multidisciplinary nature of sustainable engineering, where different fields intersect and collaborate to achieve sustainable solutions.

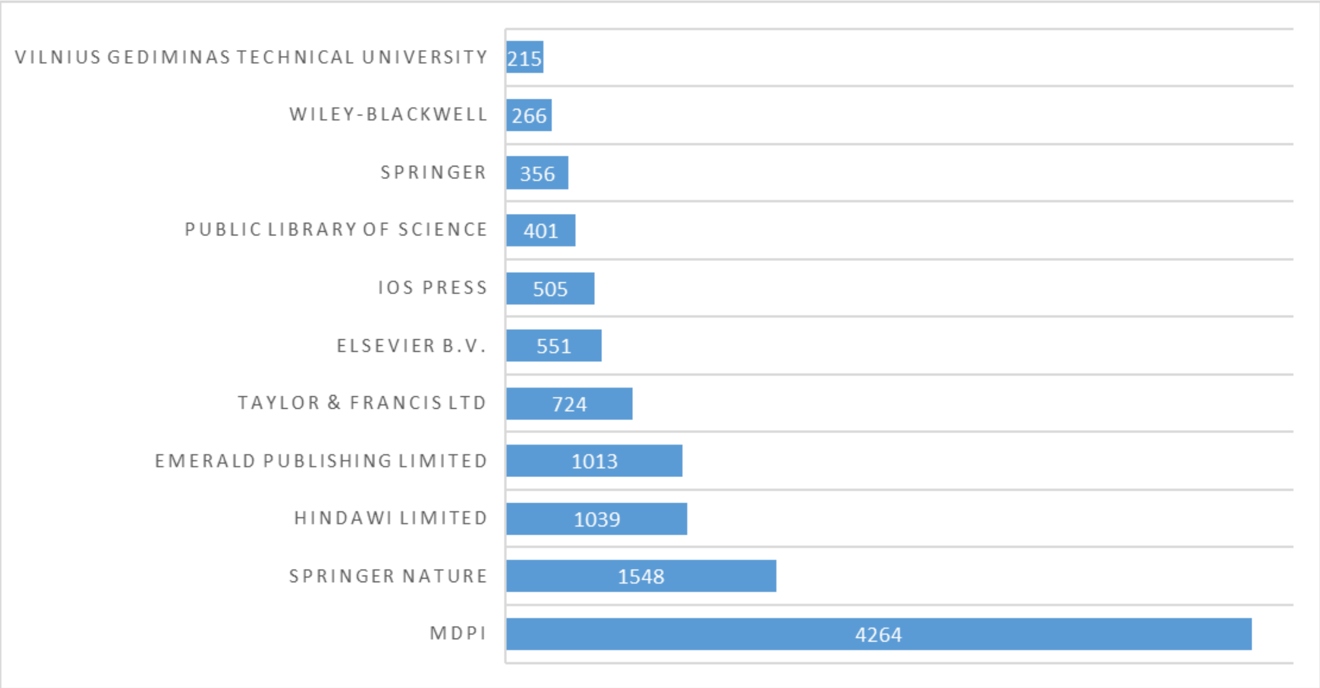

Figure 1. Publishers of articles pertaining to the use of MCDM methods in sustainable engineering.

The journal Sustainability has the most publications on the topic, with 2290 articles, followed by the Journal of Intelligent & Fuzzy Systems and Mathematical Problems in Engineering, with 440 articles each (Figure 2). PLoS ONE and Energies also have a significant number of publications, with 401 and 220 articles, respectively. The topics covered by the publications include environmental management, energy production and consumption, transportation, water management, and quality and reliability management, among others. The use of MCDM methods allows for the consideration of multiple criteria in decision-making, which is considered essential in achieving sustainability in engineering practices.

The assortment of literature pertaining to the application of MCDM methods in sustainable engineering covers a wide range of subjects, as shown in the list of the most frequent keywords (Figure 3). Decision-making and MCDM are the most common subjects, with a total of 1433 and 1318 articles, respectively, followed closely by the analytic hierarchy process (AHP), with 1293 articles. Sustainability, sustainable development, fuzzy sets, and supply chains are also important subjects, with over 500 articles each. Other notable subjects include risk assessment, renewable energy sources, geographic information systems, fuzzy logic, and multi-criteria decision-making. The literature also covers specific applications such as company business management, construction projects, logistics, waste management, water supply, and power resources. The research regarding the use of MCDM methods in sustainable engineering is diverse and covers a wide range of subjects, reflecting the broad scope of sustainable engineering as a field of study.

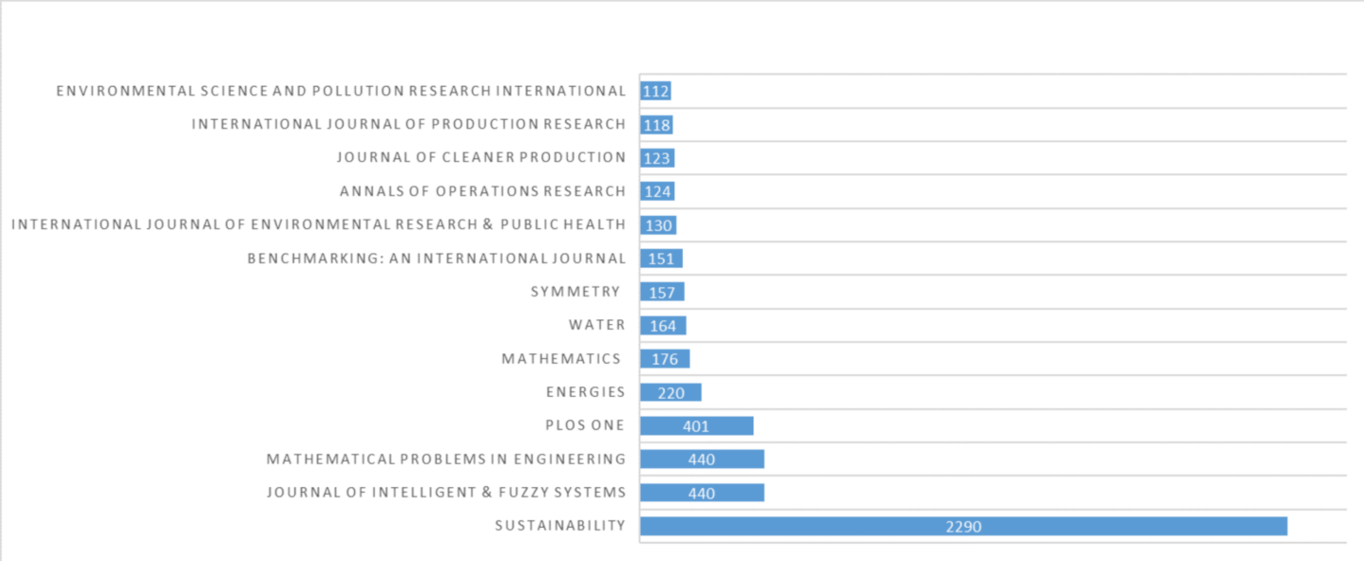

Figure 2. Publications of articles pertaining to the the use of MCDM methods in sustainable engineering.

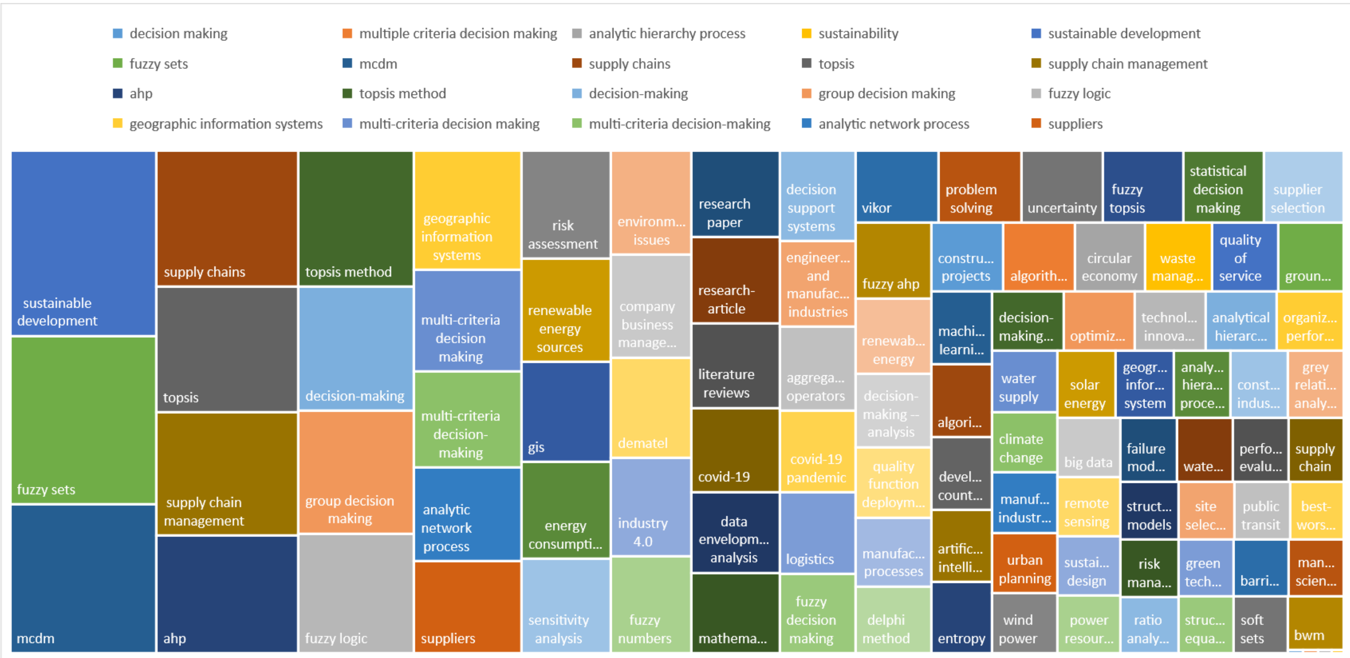

Figure 3. Subjects of articles pertaining to the use of MCDM methods in sustainable engineering.

In sustainable engineering, the researched literature demonstrates that the researchers have frequently employed MCDM methods to address complex decision-making challenges. AHP has been the most frequently used method, with 1986 articles published, followed by TOPSIS (939), ANP (281), and DEMATEL (227). DEMATEL, BWM, and VIKTOR have been used in sustainable engineering, with 227, 174, and 168 articles published, respectively. Finally, Fuzzy sets have been widely used in various fields, with 1471 articles published, and Fuzzy AHP and Fuzzy TOPSIS are also popular. These methods (Figure 4) have been used to address various decision-making problems in sustainable engineering, ranging from environmental management to energy management.

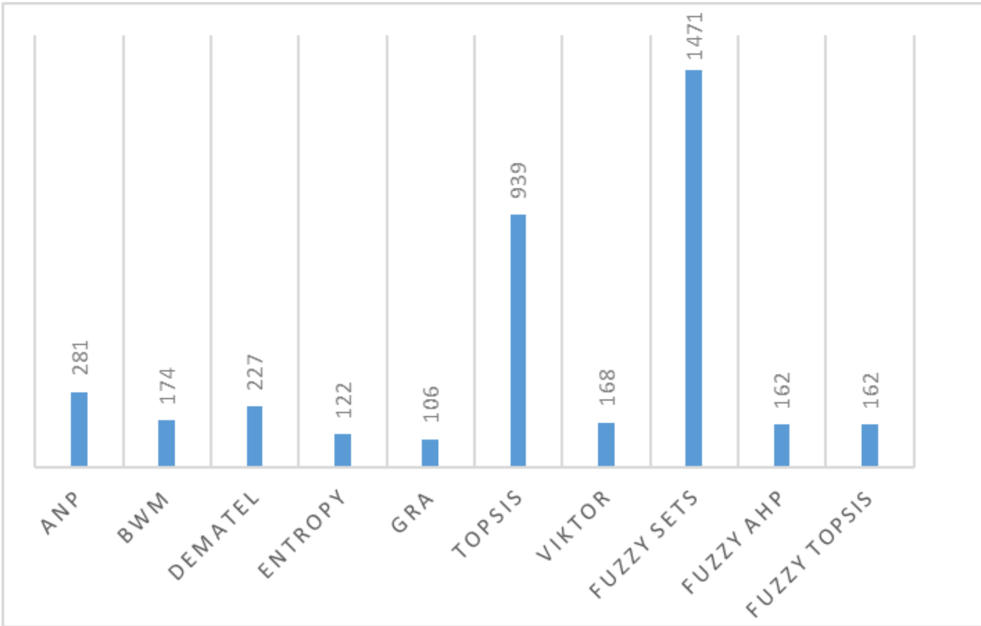

Figure 4. The most commonly used methods in the sustainable engineering articles.

4. Detailed Review Results

4.1. Sustainable Engineering

Sustainable engineering is a multidisciplinary approach [7] to designing and managing engineering systems that meets the demands of present-day society without jeopardizing future generations' ability to meet their specific requirements. The concept of sustainability has its roots in environmentalism and conservationism [11], but it has evolved to encompass social and economic aspects as well [12]. Sustainable engineering considers the environmental, social, and economic impacts of engineering systems throughout their entire life cycle, from design and construction to operation and decommissioning [13,14]. The goal of sustainable engineering is to create systems that are resilient [15–17], adaptive [18], and regenerative [19], and that contribute to the well-being of humans and the planet.

The principles of sustainable engineering include minimizing resource use and waste generation, reducing carbon emissions and other environmental impacts, enhancing social equity and inclusion, promoting economic prosperity and resilience, and embracing systems thinking and innovation [20–22]. Sustainable engineering is essential in contemporary engineering practice as it addresses the challenges of climate change, resource depletion, population growth, and urbanization, and contributes to the fulfillment of the Sustainable Development Goals established by the United Nations [23,24].

The use of MCDM methods in sustainable engineering is motivated by the need to make informed decisions that balance environmental, social, and economic considerations, and that account for the interdependencies of different criteria and stakeholders. MCDM methods provide a systematic and transparent approach to evaluating alternatives and trade-offs, considering multiple criteria and preferences, and identifying the most preferred options [25]. The use of MCDM methods in sustainable engineering has increased in recent years due to advances in computing power, data availability, and stakeholder engagement, as well as the growing recognition of the significance of sustainability in engineering practice [26].

MCDM methodologies have been adopted in various areas of sustainable engineering, including energy systems [27–31], transportation systems [32–36], water and wastewater systems [37–41], building design and construction [42–46], and industrial processes [47–51]. These applications aim to identify the most sustainable options among a set of alternatives, considering various criteria and stakeholders' preferences. For example, different MCDM methods were put to use to identify the most adequate renewable energy technology for a given location, considering technical, economic, environmental, and social criteria [31]. MCDM methods have also been used to identify the sustainability performance of buildings and infrastructure projects, considering criteria such as energy efficiency, carbon emissions, water use, and social and economic impacts [44].

The outcomes of these applications have shown that MCDM methods can provide valuable insights into the sustainability trade-offs and synergies among different criteria and alternatives, and can support informed decision-making that balances environmental, social, and economic considerations. However, the success of MCDM methods in sustainable engineering depends on the quality and availability of data, the validity and reliability of the criteria and indicators used [52–54], and the participation and engagement of stakeholders in the decision-making process [55–57]. To address these challenges, ongoing research is focused on developing more sophisticated MCDM methods that can handle complex and uncertain data, incorporate dynamic and feedback processes, and integrate qualitative and quantitative information [58–62].

4.2. MCDM Methods

MCDM methods are a set of tools used to evaluate alternatives that satisfy multiple criteria or objectives. In sustainable engineering, MCDM methods are widely used to support decision-making processes that involve complex and conflicting criteria such as environmental impact, economic viability, social equity, and technological feasibility. MCDM methods aim to provide an organized and transparent framework for assessing alternatives by considering a variety of criteria and identifying the most preferred alternative.

There are many different MCDM methods, each with its own set of theoretical foundations and applications. Some of the most commonly used MCDM methods in sustainable engineering are listed hereinafter.

The Analytic Hierarchy Process (AHP), developed by Thomas L. Saaty in the 1970s, is a widely used method for decomposing a complex decision problem into a hierarchy of simpler sub-problems and evaluating the relative importance of each criterion and alternative [63]. AHP is particularly useful when the decision problem is complex and involves a large number of criteria and alternatives [64]. AHP has been used in 1986 articles pertaining to the application of MCDM in sustainable engineering, indicating its popularity.

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), developed by Hwang and Yoon [65], is a method for ranking alternatives based on their distance from the ideal solution to the worst solution. The TOPSIS has been widely used in various fields, including sustainable engineering, with 939 articles on its application in MCDM methods.

Fuzzy sets are used to represent imprecise and uncertain information in decision-making processes [66]. Fuzzy logic, which is based on fuzzy sets theory, is useful for handling uncertainty and imprecision in decision-making [67]. Fuzzy sets and fuzzy logic have been used in 1471 articles pertaining to the application of MCDM in sustainable engineering. Fuzzy AHP and Fuzzy TOPSIS are two commonly used extensions of AHP and TOPSIS that incorporate fuzzy sets.

The Analytic Network Process (ANP), developed by Saaty [68], is a generalization of the AHP that can model feedback and dependence among criteria and alternatives [69]. The ANP has been used in 281 articles pertaining to the application of MCDM in sustainable engineering.

The Decision-Making Trial and Evaluation Laboratory (DEMATEL), developed by Gabus and Fontela [70], is a method for modeling and analyzing the causal relationships between criteria and alternatives [71]. The DEMATEL has been used in 227 articles pertaining to the application of MCDM in sustainable engineering.

The Best Worst Method (BWM), developed by Rezaei [72], is a method for evaluating and ranking alternatives based on their best and worst performance with respect to a set of criteria [73]. The BWM has been used in 174 articles pertaining to the application of MCDM in sustainable engineering.

The VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method, published by Duckstein and Opricovic [74], is a method for ranking and selecting alternatives based on their proximity to the ideal and anti-ideal solutions. VIKOR has been used in 168 articles pertaining to the application of MCDM in sustainable engineering.

Grey Relational Analysis (GRA), developed by Deng [75], is a method for analyzing and ranking alternatives based on their similarities and differences with respect to a reference alternative. GRA has been used in 106 articles pertaining to the application of MCDM in sustainable engineering.

The entropy method is a method for weighting criteria based on their relative importance and uncertainty [76]. It has been used in 122 articles pertaining to the application of MCDM in sustainable engineering.

Each MCDM technique has its own strengths and weaknesses, depending on the specific problem and application. The choice of MCDM technique depends on the specific problem and application, as well as the availability of data, and stakeholder preferences [77]. Therefore, it is essential to carefully evaluate the strengths and weaknesses of each technique and select the most appropriate one for the given problem and context.

In addition to the specific problem and application, the availability of data and expertise can also influence the choice of MCDM technique. For example, some MCDM methods, such as AHP and TOPSIS, require pairwise comparison matrices [78] that may be difficult to obtain or may involve subjective judgments. Other methods, such as fuzzy logic and entropy, can handle uncertain and imprecise information, but may require significant expertise in fuzzy set theory or information theory [79]. Therefore, it is important to consider the availability and quality of data and expertise when selecting an MCDM technique.

Stakeholder preferences can also influence the choice of MCDM methods. Different methods may be more suitable for different types of stakeholders or decision contexts. For example, PROMETHEE and ELECTRE are particularly useful for handling conflicting preferences and priorities among stakeholders [80], while fuzzy logic can be useful for representing vague or ambiguous preferences [81]. Therefore, it is important to include stakeholders in the decision-making process and consider their preferences and perspectives when selecting an MCDM technique. By carefully evaluating the strengths and weaknesses of each technique and selecting the most appropriate one for the given problem and context, decision-makers can make more informed and effective decisions that balance multiple criteria and objectives.

4.3. Case Studies: Applications of MCDM Methods in Sustainable Engineering

In this section, exemplary case studies of real-world applications of MCDM methods in sustainable engineering are presented. The presented case studies aim to provide a deeper understanding of how MCDM methods could be utilized to address complex decision-making problems in different areas of sustainable engineering.

MCDM methods have been frequently employed in various areas of sustainable engineering to support decision-making that considers multiple criteria and stakeholders' preferences. In this section, we will discuss some specific examples of MCDM applications in energy, manufacturing, transportation, and environmental engineering, highlighting the criteria considered and the outcomes achieved.

For example, energy engineering is an area where MCDM methods have been extensively utilized to determine the most sustainable options among different renewable and non-renewable energy sources [82–84], considering technical, economic, environmental, and social criteria. For instance, MCDM methods have been used to select the most appropriate renewable energy technology for a given location, taking into account factors such as resource availability, technical feasibility, economic viability, and social acceptance. These methods have been applied to various renewable energy sources, including solar, wind, geothermal, and hydroelectric power. The outcomes of these applications have shown that MCDM methods can provide valuable insights into the trade-offs among different criteria and help identify the most sustainable options. Additionally, a study by

Alhakami [85] addresses the need for a comprehensive security evaluation approach and proposes an MCDM methodology to assess security risks in power control technology and communication networks of energy management and control systems.

Manufacturing and production engineering is another area in which MCDM methods have been used to support sustainable decision-making. For example, MCDM methods have been used to evaluate the sustainability performance of manufacturing processes, considering criteria such as energy efficiency, waste generation, water use, and social and economic impacts [86–88]. These methods have also been applied to support product design and development [89–91], considering criteria such as material selection, energy consumption, and end-of-life disposal. The outcomes of these applications have shown that MCDM methods can help to identify the most sustainable manufacturing processes and products and support the transition towards a circular economy. Furthermore, applying these methods in the specific context [92] can enhance sustainable decision-making practices.

Transportation engineering is a critical area for sustainable engineering as transportation systems are responsible for a significant portion of greenhouse gas emissions and other environmental impacts [93]. MCDM methods have been used to support decision-making in transportation engineering [94–96], considering criteria such as energy efficiency, emissions reduction, safety, and social and economic impacts. For example, MCDM methods have been used to evaluate the sustainability performance of different modes of transportation, such as cars [97], buses [98], trains [99], and airplanes [100], and to identify the most sustainable options for a given transportation problem. These methods can also be applied to support the design and planning of transportation infrastructure, such as roads [101], bridges [102], and airports [103], considering criteria such as energy consumption, environmental impacts, and social and economic benefits, and even assess potential suppliers based on their ability to address specific challenges such as the COVID-19 epidemic [104]. Furthermore, MCDM methodologies are also proposed to monitor customer satisfaction in the airline service industry, aiming to enhance service quality and meet consumer expectations [105].

Environmental engineering is a broad area that encompasses various disciplines, such as water and wastewater treatment, air pollution control, and solid waste management. MCDM methods have been used to support decision-making in environmental engineering, considering criteria such as environmental impacts, economic costs, and social benefits. For example, MCDM methods have been used to identify the most sustainable options for water and wastewater treatment [106–110], considering criteria such as treatment efficiency, energy consumption, and social acceptance. These methods can also be applied to support the management of solid waste [111], considering criteria such as waste reduction, recycling, and disposal options. In a similar manner, the evaluation of environmental quality in specific contexts [112] utilizes fuzzy MCDM methods incorporating multiple factors to guide decision-making in environmental protection research and future renovation planning, and the compatibility between MCDM methods in assessing erosion risk highlights the fuzzy methods as an effective tool for evaluating erosion risk in semi-arid areas and guiding erosion prevention actions [113].

The applications of MCDM methods in sustainable engineering have shown that these methods can provide valuable insights into the sustainability trade-offs and synergies among different criteria and alternatives, and can support informed decision-making that balances environmental, social, and economic considerations. However, the success of these applications depends on the quality and availability of data, the validity and reliability of the criteria and indicators used, and the participation and engagement of stakeholders in the decision-making process.

5. Challenges and Future Directions

MCDM methods face several challenges when applied to sustainable engineering problems. One of the key challenges of MCDM methods is the availability and quality of data. Sustainable engineering problems often involve multiple criteria and sources of information [114], and it can be difficult to obtain reliable data that represent the complexity of the problem. In addition, the data may be incomplete, inconsistent, or subjective, which can affect the decision-making process' reliability and accuracy [115].

Another challenge of MCDM methods is model uncertainty. Many of these methods are based on mathematical models that may not accurately reflect the complexity and dynamics of sustainable engineering problems [116]. This can lead to errors in the estimation of criteria weights, rankings, and overall scores, which can affect the credibility and acceptability of the decision-making process.

MCDM methods also face challenges related to stakeholder engagement. Sustainable engineering problems often involve multiple stakeholders with different perspectives, values, and interests [117]. It can be difficult to engage stakeholders effectively in the decision-making process and to ensure that their voices are heard and their concerns are addressed. In addition, stakeholders may have different levels of expertise and understanding of the decision-making process and the MCDM approaches employed, which can affect the quality and acceptability of the decision.

Despite these challenges, MCDM methods have an opportunity to be vital in sustainable engineering practice. One promising research direction is the blend of MCDM methods, artificial intelligence (AI), and machine learning (ML) methods. AI and ML may enhance the accuracy and efficiency of the decision-making process by enabling the automated processing and analysis of large and complex data sets [118]. The combination of MCDM methods with AI and ML can also facilitate the incorporation of expert knowledge, uncertainty, and risk into the decision-making process.

Another future research direction is the incorporation of dynamic and complex systems into the decision-making process. Many sustainable engineering problems involve complex systems that are characterized by non-linear relationships, feedback loops, and emergent properties. MCDM methods can be further developed to account for these complexities by incorporating methods such as system dynamics, agent-based modeling, and network analysis.

A third future research direction is the enhancement of multi-stakeholder decision-making. This involves developing MCDM methods that can facilitate effective stakeholder engagement by incorporating methods such as participatory decision-making, collaborative modeling, and multi-criteria deliberation. The development of user-friendly and transparent decision support tools can also help to enhance stakeholder engagement and improve the acceptability the process of making decisions.

Finally, upcoming research can concentrate on the development of user-friendly and transparent decision support tools. MCDM methods can be complex and difficult to understand for non-experts, which can limit their use in practice. User-friendly and transparent decision support tools can help to bridge this gap by providing intuitive and accessible interfaces, visualizations, and explanations.

MCDM methods have an important function in encouraging sustainable engineering practices. However, to realize their full potential, it is essential to address the challenges and limitations they face and explore new research directions that can enhance their effectiveness and applicability in real-world decision-making contexts.

6. Conclusions

This review has provided a comprehensive overview of the applications of MCDM methods in sustainable engineering. The review discussed the theoretical foundations and applications of various MCDM methods, including their strengths, weaknesses, and comparisons. It also highlighted the importance of sustainable engineering and discussed the different areas in which MCDM methods have been applied, such as energy, manufacturing, transportation, and environmental engineering. Furthermore, this review presented case studies of real-world applications of MCDM methods in sustainable engineering and analyzed the main findings and implications for engineering practice. Finally, the review discussed the challenges and limitations of MCDM methods in sustainable engineering and proposed future research directions to enhance their effectiveness and applicability.

The review has demonstrated that MCDM methods have the potential to address complex decision-making problems in sustainable engineering by considering multiple criteria and stakeholder perspectives. However, the effective implementation of these methods requires issues related to data availability, model uncertainty, and stakeholder engagement to be addressed. Future research directions include the development of more robust and transparent MCDM models, the integration of new data sources, and the incorporation of emerging technologies such as artificial intelligence and machine learning. The findings of this review have important implications for engineering practice and research and can inform the development of more sustainable and efficient engineering solutions in the future.

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