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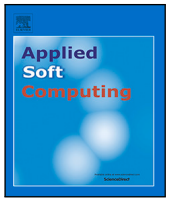

Sensitivity analysis approaches in multi-criteria decision analysis: A systematic review

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ABSTRACT

In the field of Multi-Criteria Decision Analysis (MCDA), the deployment of sensitivity analysis has become a fundamental approach to testing the robustness and reliability of the results obtained. Its importance lies in its ability to gain additional insight into potential changes that affect the desirability of the decision variants being evaluated. Through different methodologies, it reveals the vulnerability of results to changes in the underlying data, thus offering valuable information to support decision making. This research paper highlights a compendium of 250 researches involving the application of sensitivity analysis in a multi-criteria context. Using a structured approach of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, this study provides a comprehensive review process. The main objectives are to identify and categorize common sensitivity analysis techniques explained in the literature and to describe a selected framework that facilitates the execution of these techniques. The research demonstrates the importance of sensitivity analysis to enhance the credibility of MCDA outcomes and contributes to the field of decision support.

1. Introduction

Multi-Criteria Decision Analysis (MCDA) is a group of techniques that propose solutions to evaluate decision variants concerning a set of criteria in a structured manner [1]. These methods are essential in Decision Support Systems (DSS), which aim to support the decision-maker in making rational choices based on available data [2]. The main assumption of MCDA methods is the use of input data specifying the objective of the type of criteria, their relevance, and the specification of decision variants regarding these parameters. Then, subsequent steps and mathematical transformations determine a preference value for the alternatives describing their attractiveness relative to the other options. This methodology is advantageous and helpful to the decision-maker in cases where the problems under consideration are complex and contain multiple criteria or decision variants [3]. These are the cases where the decision-makers' analytical capabilities are decreasing, and systems based on MCDA methods guarantee rapid and effective calculation of results. An additional advantage of such systems is the repeatability of the calculations performed and the lack of influence of external factors on the results, which often cannot be avoided by relying solely on expert knowledge [4]. Each method proposed within the MCDA group is characterized by a distinct approach to obtaining the final result [5,6]. Consequently, they rely on different metrics in their calculations, which can be applied universally regardless of the method [7]. A popular approach is using different data normalization methods [8,9], subjective and objective criterion weighting techniques [10–12], distance metrics [13], or data defuzzification in a fuzzy environment [14–16].

A frequently used technique in multi-criteria calculations is sensitivity analysis [17]. It allows the test of the robustness of the results against certain changes [18]. Moreover, sensitivity analysis explores the relationship between the output and the input of the process [19]. When developing DSSs based solely on MCDA methods, it should be borne in mind that an expert using such a system will not have comprehensive knowledge of possible changes in the input data and their impact on the final results. There are often slight differences in preference values between the decision variants evaluated [6,20]. It indicates their similar attractiveness, so it is worthwhile paying additional attention to indicating possible changes in rankings resulting from modifications in the model input parameters. It is precisely where sensitivity analysis operates. The decision support models using its

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assumptions are complete, providing comprehensive knowledge and more significant support for the decision-maker [21].

It is also worth mentioning that sensitivity analysis is a research approach used in various fields [17]. It is a versatile technique that allows searching for possible solutions, making it useful for many studies. There are literature reviews on sensitivity analysis showing its application in selected areas. Pamucar and Biswas addressed the problem of comparing the market performance of metaverse crypto assets with a novel hybrid decision-making framework with a sensitivity analysis used to examine the stability of the results [22]. Mahmutagić et al. directed their research to assess the efficiency of forklifts in warehousing systems with different weight values to examine their impact on the results [23]. Pang et al. provided a systematic review of the sensitivity analysis for building application [24]. The authors presented the pros and cons of the mainstream methods for sensitivity analysis and practical advice on method selection. Pianosi et al. in 2016, showed a systematic review with practical workflow concerning the sensitivity analysis of environmental models [25]. The authors have provided practical guidelines, discussed critical choices, and given examples from the literature to highlight trends. In 2005 Saltelli et al. presented an overview of the applications of sensitivity analysis in chemical models [26], while Baio and Dawid in 2015 directed their research towards showing the applications of probabilistic sensitivity analysis in health economics [27]. Rao and Sujatha addressed the problem of selection of healthcare waste treatment technology selection, testing the results' robustness with different sets of criteria weights [28]. Moreover, the combination of MCDA and sensitivity analysis assumptions can be found in the decision models directed to solve problems connected to renewable energy development [29,30], material selection [31,32], transport [33–35], and sustainability [36,37], among others. Many works are directed towards emphasizing the role of sensitivity analysis in various fields. However, there is a clear research gap in the area of decision-making combined with sensitivity analysis. Literature reviews focus on selected fields of operation or are outdated and do not consider new research and directions for applying sensitivity analysis in decision-making.

Rappaport in 1967 presented the sensitivity analysis in decision-making [38], which corresponds to the topic described. However, this review was done many years ago and thus did not follow the new research approaches. One can also find reviews on spatial decision-making [39], economic evaluation [40], or power systems [41]. However, these works do not cover the problem comprehensively, and they are focused on the targeted use of decision-making methods in combination with sensitivity analysis. Therefore, it is worth proposing a review considering new research approaches to show the current use of sensitivity analysis in decision-making.

This paper presents a comprehensive review of sensitivity analysis approaches in decision-making problems, addressing a notable research gap in the current literature. Utilizing the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology [42], the study systematically reviews the intersection of sensitivity analysis and Multi-Criteria Decision Analysis (MCDA). Through a rigorous review process, the paper categorizes and describes various sensitivity analysis techniques, offering insights into their strengths and limitations. The primary contribution lies in its systematic classification of sensitivity analysis classes, aiding researchers and practitioners in selecting appropriate approaches for specific decision-making problems. Ultimately, this study not only synthesizes existing knowledge but also provides a practical guide for navigating sensitivity analysis in decision-making contexts. The main contributions of the study are:

- systematizing knowledge of sensitivity analysis techniques used in decision-making
- indicating the advantages and disadvantages of available solutions
- presenting classifications of sensitivity analysis classes
- indicating the selection process of sensitivity analysis approaches to given decision problems

The rest of the paper is organized as follows. Section 2 presents the overview of current knowledge in the field of sensitivity analysis in decision-making concerning the PRISMA review methodology. Section 3 shows the classification of sensitivity analysis approaches identified based on the literature review. Section 4 describes the selected sensitivity analysis frameworks and presents the use-case scenarios in which the presented frameworks can be applied. Section 5 shows the discussion regarding the performed research. Finally, in Section 6, the conclusions are drawn from the research, and the summary is presented.

2. State of the art: PRISMA methodology

Since PRISMA covers multiple areas of the review process and is determined to address problems in general for multiple research areas, some of the proposed steps could not be used in reviews undertaken in given fields. The selection of the steps from the PRISMA methodology was based on limiting the proposed review stages to cover only the most important elements since the proposed review of Sensitivity analysis in the MCDA field aimed to provide additional information on the sensitivity analysis classification and sensitivity analysis frameworks descriptions, which extend the scope of the conventional PRISMA methodology. Thus, it was decided to use the modified PRIMA methodology to fulfill the assumptions made. Six steps of the standard PRISMA flow were used in this review, with their description presented below.

2.1. Information sources

The Mendeley platform was used as an information source. It is a comprehensive tool for searching for academic papers that have already been published in specific research areas. It includes access to articles from a wide range of disciplines, and the search itself is based on matching keywords from the manuscripts with phrases provided by the user. The Mendeley application continuously updates existing databases with newly published papers. It ensures its users can access the latest research trends in chosen areas. However, several other tools for searching papers in academic research databases exist, such as Scopus, Web of Science (also known as Web of Knowledge), ScienceDirect, and IEEE Explore. The first three of the mentioned have multidisciplinary databases, while the last one is dedicated to the field of Engineering. The tools listed are alternatives to the one used in this review. However, the final choice was determined by the ability to control the reviewed references in the Mendeley tool and the convenient way to export and manage items. Moreover, it has a simple, straightforward, and intuitive structure that provides convenient access to scientific papers in the selected area.

2.2. Search strategy

To filter out papers directed to topics related to the study of the impact of sensitivity analysis on the results of multi-criteria decision analysis, selected keywords were used to narrow down the search area. Phrases such as:

- `sensitivity analysis mcda`,
- `sensitivity analysis decision making`,
- `sensitivity analysis fuzzy decision making`

were used. The provided keywords served as a means of filtering the records available in the Mendeley platform database, and allowed for a search of the available database to retrieve published research articles in the area of sensitivity analysis combined with a particular field of decision-making. Since the sensitivity analysis approach is widely used in multiple research fields, it was necessary to focus the search process

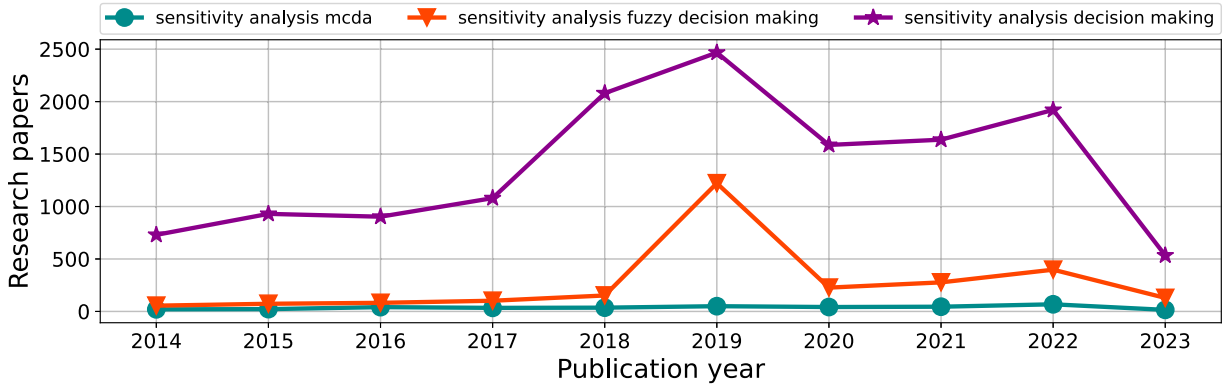

Fig. 1. Amount of research papers in years 2014–2023 regarding different keywords used in Mendeley database.

on the area of decision-making. It provided the opportunity to create an overview fully committed to the given topic and highlight currently used research methodologies.

The keywords used in the search strategy were selected based on their precise reflection of the area of the review that was performed, namely the Multi-Criteria Decision Analysis in a crisp and fuzzy environment (used phrases of `mcda`, `decision making`, and `fuzzy decision making` as a part of the keywords), and Sensitivity Analysis techniques (`sensitivity analysis` phrase in the proposed keywords. Using selected keywords allowed for searching for the articles in this particular area while limiting the potential area of reviewed papers that could be more complex and not directly connected to the field if more keywords were used. They also allowed for general but focused on the field of decision making and sensitivity analysis searching, which could not be achieved by using particular MCDA techniques or sensitivity analysis approaches in the keywords.

2.3. Data items

The selection process was focused on choosing research papers directed to any area of application in multi-criteria decision analysis problems combined with sensitivity analysis. It was assumed that this review would consider the general use of the mentioned techniques, regardless of the application area. Since currently available reviews connected with this field are based on comparing research approaches used in the particular class of problems, it was worthwhile to broaden the view and combine research works from different fields of application to compare the used methodologies and provide a general view on those techniques. This approach was driven by a desire to compare how sensitivity analysis techniques are used in current multidisciplinary research. The focus was on articles published after 2014 to provide an overview of the up-to-date research approaches. Given the rapid evolution of the decision-making field, marked by the emergence of novel techniques and research methodologies, our choice to incorporate the latest publications within the scope of the proposed review is geared towards spotlighting the contemporary strategies employed in multi-criteria assessments, coupled with sensitivity analysis of the outcomes. In addition, all scientific papers were considered, regardless of paper authors, publishers, impact factor, or the number of citations. The selection of articles for the review was also not influenced by the method and type of research funding.

2.4. Study selection

Using the search approaches described above, it was possible to filter the records in a way to narrow the scope of the search to the topic of decision-making in combination with sensitivity analysis. Fig. 1 shows a diagram of the number of scientific article searches depending on the keywords used for the Mendeley application database. The flow of the graph shows that the most matches in the database were found for the keywords: `sensitivity analysis decision making`. In 2019, there were nearly 2500 research papers that met the requirement of matching for the provided search keyword. On the other hand, it can also be seen that the number of published papers in this area increased from 2014 to 2019. Consequently, it can be inferred that interest in the topic of sensitivity analysis in decision-making was becoming an increasingly important issue. In 2020 and 2021, fewer papers were published, but still at a higher level than up to 2017. For 2022, an increase in the number of published papers can be seen.

Furthermore, in 2023 there is a visible decrease in the matched articles, but this is related to considering already published papers and the ongoing publication procedure of scientific articles that may be available at the end of this year. Moreover, it can be seen that there is a noticeable growth of matched scientific papers in 2019 for the *sensitivity analysis fuzzy decision making* keyword, where nearly 1200 research works were observed. On the other hand, the keyword *sensitivity analysis mcda* guaranteed the least matches from the proposed search phrases. It can be caused by the fact, that this keyword contains an abbreviation for Multi-Criteria Decision Analysis (MCDA), which may be not used in the manuscript titles or keywords section as frequently as the full name of those techniques. However, it can be seen that still numerous works are directed into the problems concerning decision-making with sensitivity analysis which confirms that this field is being constantly examined and developed.

The presented review concerns 250 research articles directed to problems of decision-making and sensitivity analysis. To present the currently used solutions in this field, the papers included in the review were published between 2014 and 2023. Fig. 2 presents the cumulative distribution of research papers included in the review throughout the given period. It can be seen that most of the works were published between 2020 and 2021. More than half of the works included in the review were presented in this period. This offers an up-to-date overview of the currently used methodologies and sensitivity analysis approaches. To provide access to the research papers considered in the review, the works stored in the Mendeley database were exported to files in *.ris* and *.bib* formats and are available in an open repository [43].

The review aims to comprehensively cover a specific topic of sensitivity analysis in decision-making problems, including various perspectives, methodologies, and findings. Using a larger number of papers helps provide a more comprehensive overview of the subject matter. Moreover, after reviewing a certain number of papers, we observed a saturation point where new papers did not significantly add novel insights or information to the discussion. Based on that, we decided to include 250 papers, which constitute a representative sample that adequately captures the key themes and trends in the field.

During the review process, the items were categorized and described regarding the used approaches for multi-criteria evaluation, sensitivity analysis techniques, or the problem that was taken into consideration.

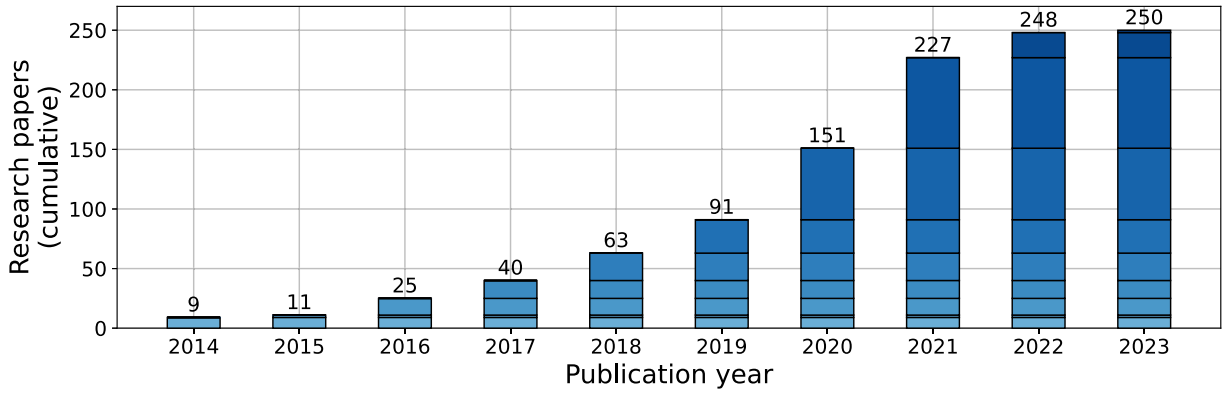

Fig. 2. Distribution of the type of application of sensitivity analysis in decision-making in 250 reviewed scientific papers.

Based on that, it was possible to establish the distribution of the research papers taking into account the specific application field. Fig. 3 presents the visualization of the reviewed research papers' distribution regarding the research field to which the work was directed (A) and the approach used for the results sensitivity analysis (B). The first graph (A) shows that the most significant field concerned in the papers from the review was devoted to sustainability problems (39.6%), which is currently a highly popular and important issue. The second largest field was identified as GIS-related (Geographic Information System) problems (19.6%), while the third visible area of application was Healthcare (14.0%). The rest of the papers were directed into various fields and were classified as the Others group (26.8%). It includes works related to housing locations [44], advertisements [45], transport infrastructure [46], and education [47], among others. It can be seen that the decision models with sensitivity analysis are applied to various multi-criteria problems and thus, extending the fields of practical potential of those systems.

The second graph (B) presents the distribution of the sensitivity analysis approaches used in the decision models encountered in the reviewed papers. The significant majority of the use cases are covered by the approaches based on changing the criteria weights (77.2%). The other distinct approach is identified as changing the values describing the alternatives, which translates into making modifications in the decision matrix (6.8%). However, this approach is nearly 12 times less popular than the first technique. The rest of the techniques for performing the sensitivity analysis are grouped together and labeled as Others (16.0%). Those approaches consider applying Monte Carlo Simulation [48], Variance-based sensitivity analysis [49], Sobol'-MCDA [50], or modifying methods parameters for Visekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) [51], or TODIM (an acronym in Portuguese for Interactive and Multicriteria Decision Making) [52].

2.4.1. Application fields of MCDA models using sensitivity analysis

As the distribution of subjects covered by the articles included in the review shows, decision models using sensitivity analysis are employed in many areas. Based on the research papers from the review, it has been possible to identify three distinctive practical areas in which attempts are being made to determine the most rational choices of decision variants.

2.4.1.1. Sustainability decision problems.

The first of these is the area of sustainability problems. Due to increasing demands on the solutions used in various industries to reduce negative environmental impacts, use more sustainable and efficient materials, or minimize risks, special attention is being given to systems designed to increase their efficiency. The sensitivity analysis of solutions applied in this area makes it possible to indicate whether other decision variants can replace the potentially most attractive choices in specific cases of changes in input parameters. Researchers use a variety of techniques to achieve the intended result of determining the robustness of results to modifications. Wu et al. directed their research to optimal site selection for distributed wind power [53]. The model was based on Triangular Intuitionistic Fuzzy Numbers and the Fuzzy TODIM method, while the robustness of the results was examined by applying a modification of criteria weights by ±10% and 20% for each weight subsequently. Stoycheva et al. [54] proposed an MCDA framework for sustainable manufacturing in the automotive industry using Multi-Attribute Value Theory (MAVT). Since the determined model was structured for main and lower-level criteria, every criterion for the main-level criteria was used in sensitivity analysis to change subsequent weights and verify its influence on the results. Zyoud et al. used Fuzzy AHP and Fuzzy TOPSIS methods to determine a framework for water loss management [55]. The authors applied the sensitivity analysis by using 45 combinations of weights representing the importance of criteria in the decision problem. Taylan et al. evaluated the energy systems using Fuzzy AHP, Fuzzy VIKOR, and Fuzzy TOPSIS [56]. Two sensitivity analysis approaches were used to verify the robustness of the results. Firstly, the v parameter in the Fuzzy VIKOR method representing the weight of maximum group utility was modified. Secondly, the Fuzzy Data Envelopment Analysis (DEA) was used with the combination of the Fuzzy VIKOR method to examine the extent to which each energy system can convert its input into outputs. Carmo et al. addressed the problem of ranking product systems considering uncertain Life Cycle Sustainability Assessment (LCSA) [57]. The authors performed a sensitivity analysis using selected MCDA methods, namely the Weighted Sum, AHP, TOPSIS, and Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) II, and compared the obtained results. Asif and Chen focused on developing a system for reducing air emissions from the mining process [58]. Combining the AHP and PROMETHEE methods for the multi-criteria assessment and Monte Carlo simulation for the probability distribution of criteria weights allowed for determining a reliable approach for selecting air pollution control solutions. Dabous et al. presented a multi-criteria decision support framework for evaluating pavement sections driven by a sustainability-informed approach [59]. The sensitivity analysis applied in the study relied on changing criteria weights. The authors indicated that this approach aimed to understand to what extent a change in the decision factors may influence the outcomes related to a proposed decision. Lin et al. proposed an approach for environmental risk mapping of potential abandoned uranium mine contamination [60]. To examine the robustness of the results, the authors used the One At A Time (OAT) approach to incrementally adjust subsequent criteria weights.

2.4.1.2. Geographic information systems decision problems.

The second identified field in which decision models with sensitivity analysis tests were used the most is Geographic Information Systems. By

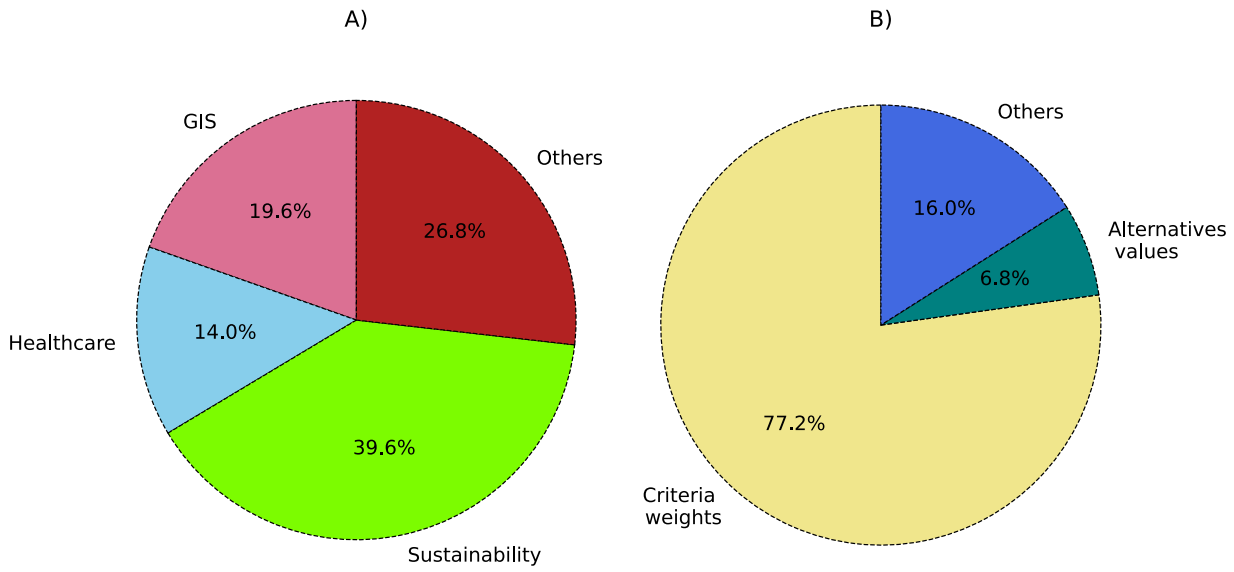

Fig. 3. Distribution of: (A) research fields; (B) the type of application of sensitivity analysis in 250 reviewed scientific papers.

employing the MCDA methods to GIS problems, it is possible to determine locations that prove to be the most satisfactory choice for given issues. Matos et al. aimed to solve the problem of selecting the most suitable compressed air energy storage reservoirs [61]. To this end, the Simple Additive Weighting (SAW) method was used to evaluate locations regarding their attractiveness. To examine the robustness of the solutions, the criteria weights values were modified by providing the percentage modification with a 5% change step. Ghorbanzadeh et al. used the Analytical Network Process (ANP) for GIS-based sensitivity and uncertainty analysis of a risk evaluation problem [49]. The authors decided to use Monte Carlo simulation and Global Sensitivity Analysis (GSA) and, more specifically variance-based approach to examine if any improvement in accuracy can be achieved by changing the criteria weights derived from the ANP method. On the other hand, de Brito et al. determined an MCDA model for flood vulnerability [62]. By applying the changes in criteria weights values, the authors aimed to indicate the vulnerability factors that are most sensitive to weight changes and cause differences in the ranking. Ayyildiz et al. directed their research to integrate AHP and Weighted Aggregated Sum Product Assessment (WASPAS) methods with Pythagorean fuzzy numbers to solve the problem of refugee camp location selection in Istanbul [63]. The sensitivity analysis was used by changing the main criteria weights to observe the potential changes in the alternatives' ranking. Ding et al. applied the Fuzzy AHP and Fuzzy TOPSIS methods to select the location of the mobility industry call center [64]. The values of global and local weights were modified to indicate the model's stability. Gao et al. determined the Multi-Criteria Decision-Making framework for large-scale rooftop photovoltaic project site selection using the Intuitionistic Fuzzy SAW and Intuitionistic Fuzzy TOPSIS methods [65]. The sensitivity analysis was focused on assessing the Decision-Makers (DM) risk attitudes and was performed in three scenarios: (1) changing the value of parameter θ from 1 to 10, (2) changing the values of α from 0 to 1, (3) and changing the value of parameter β from 0 to 1. All factors were used directly in the prospect function to adjust the performance of the model. Wang and Dang use the DEA, Fuzzy AHP, and Fuzy WASPAS for location optimization of wind plants [66]. Based on the significant level of criteria from the Fuzzy AHP method, the five most important criteria were used to analyze the influence of weights modification by ±10%, 20%, and 30%. Wu et al. presented a decision framework for selecting the offshore wind power station site [67]. By using the Intuitionistic Fuzzy PROMETHEE method and modeling the DM's attitude towards uncertainty represented by the λ parameter, it was possible to evaluate considered decision variants and indicate the robustness of the results. Pamučar et al. directed their research to logistical center location selection [68]. To this end, the selected set of MCDA methods was used, namely the COPRAS, TOPSIS, VIKOR, and ELimination Et Choix Traduisant la REalité (ELECTRE) methods. The study aimed to indicate which of the selected methods is the most resistant technique to changes in criteria weights.

2.4.1.3. *Healthcare decision problems.*

The third application problem area that was addressed in the reviewed papers was related to healthcare problems. From the performed application reviews available in the literature, it can be seen that decision systems are important in this field since they could significantly improve the quality and reliability of choices [69,70]. Wang et al. proposed an interval-valued Intuitionistic Fuzzy Jensen–Shannon divergence approach and applied it in medical diagnosis [71]. The sensitivity analysis technique considered the magnitude of the error of the decision expert. The used approach was based on defining the ϵ parameter representing the tiny error in the decision matrix, which was then added to one of the alternatives in the decision matrix, and the rest of the decision variants' values remained fixed. It represents the OAT approach with performing changes in the alternative values. Ghorui et al. proposed a model for the identification of the dominant risk factors involved in the spread of COVID-19 with Hesitant Fuzzy MCDA methodology [72]. The authors decided to modify criteria weights to identify the most significant risk factors under the Fuzzy AHP method. The problem considering the COVID-19 pandemic was also addressed by Ecer and Pamucar [73]. The Measurement of Alternatives and Ranking according to the Compromise Solution (MARCOS) technique under the Intuitionistic Fuzzy environment was used to determine the performance of insurance companies in terms of healthcare services. The stability of the model was examined by changing the criteria weights for different DMs with prepared 50 weighting scenarios. Moreover, the 50 test scenarios for criteria weights were provided which was another approach used to verify the model's robustness. The last applied sensitivity analysis test considered comparison with other Intuitionistic Fuzzy MCDA techniques. Looman et al. performed research directed at assessing primary program care for frail elderly in the Netherlands [74]. The criteria weights scenarios were compared in terms of the differences in the obtained ranking, where the criteria

relevance determined in the survey among the patients and by using the Swing weighting method were analyzed. Peters et al. attempt to determine the most attractive drinking water source selection in Southwestern Bangladesh [75]. The Monte Carlo simulation with 1000 runs was applied as the sensitivity analysis technique to determine criteria weights from a Gaussian distribution. Schug et al. used an MCDA approach to develop an efficacy-safety profile of parental analgesics used in the treatment of postoperative pain [76]. The three sensitivity analysis approaches were applied to assess: (1) the value of preference scores with a weight equal to 0 placed on opioid sparing, (2) the value of efficacy scores weighted independently from safety scores, (3) and the impact of specific criteria on overall drug performance. Reddy et al. used the AHP method for prioritizing public health guidance topics [77]. The different criteria weights scenarios were prepared to perform sensitivity analysis to indicate changes in the final ordering of the topics. Chapple et al. applied MCDA techniques to the clinical use of pharmacotherapy for overactive bladder symptom complex [78]. The sensitivity analysis was conducted by changing only benefit type criteria weights values one by one. Diaby and Goeree determined a step-by-step guide for making decisions about reimbursement in healthcare [79]. Multiple approaches to verify the models' robustness were used, for example, adjusting the value of α coefficient representing the realism factor, changing one criterion weights while adjusting the values of the other criteria, or changing the aspiration level by using the linear goal programming model, among others. Etim et al. performed an MCDA assessment of the medical waste management systems in Nigeria [80]. The AHP, Fuzzy AHP, and Fuzzy TOPSIS methods were used for this purpose. The authors provided a sensitivity analysis test based on changing the criteria weights. The weights values were altered separately between 0% and 100% to reflect the weights change in other criteria accordingly.

2.4.2. Sensitivity analysis approaches used in MCDA models

The scope of sensitivity analysis approaches can also be determined regarding the elements of the initial data that are modified. The selection of given factors and their modification can influence different areas of multi-criteria evaluation. Moreover, different conclusions can be drawn from performing such tests, allowing for taking specific actions to make the most rational choices.

2.4.2.1. Criteria weights modification.

In terms of the approaches used to analyze the sensitivity of solutions in the studies included in the review, one prominent area can be seen to have dominated. The vast majority of the work has mainly focused on analyzing the robustness of decision models to changes in the values of the criterion weights defined as inputs in the calculations. Using this approach in model stability studies allows the impact of changes in the relevance of decision parameters on potential changes in the ranking position of the decision variants under consideration to be determined. Modeling the relevance of the criteria weights also makes it possible to obtain information on emerging relationships between criteria. Despite using a research methodology to analyze sensitivity from one area, the approaches to specific tests of the robustness of solutions to change proposed by the researchers whose work was included in the review varied. Deveci focused on selecting the location for underground hydrogen storage [81]. To explore the impact of changing the criteria weights, the author changed the subsequent criteria weights from 0.1 to 1.0 while other weights remained fixed. Yazdani et al. determined a decision support framework for sustainable freight transport system evaluation [82]. The used approach of different criteria weighting considered generating 45 different scenarios, where three distinct groups were identified as criteria weights were increased respectively by 25%, 65%, and 100%. Since only one criterion weight value at a time was increased, the remaining weight values were decreased by 35%. Chang et al. developed a model for emergency plan selection using the Intuitionistic Fuzzy Multiple-Criteria Group Decision-Making approach [83]. The authors presented two ways of modeling the criteria weights. Firstly, weight values were increased by 30%. Secondly, those values were decreased by 60%. One criterion weight value was modified at a time. Thus, it was necessary to adjust the rest of the criteria weights to meet the requirement of weights summing up to 1. It produced 24 experiments to conduct, and the obtained rankings were compared regarding the occurred differences. Xu and Dong conducted a comprehensive assessment of sustainable ammonia production systems [84]. The authors considered 12 decision factors and reassigned the initial equal weights to subsequent criteria with the value of 0.23, and the rest of the weights were set with equal values as 0.07. A similar approach of sensitivity analysis examination was used by Panchal et al. to select sustainable oil for cleaner production in Indian foundry industries [85]. The weight value corresponding to the emission factor was set to 0.60, while other criteria weights were given equal weights. Moreover, the authors used the same approach to model the particular sub-criterion by adjusting the values of the rest of the sub-criteria. Dogan addressed the research on selecting process mining technology using the Fuzzy AHP method [86]. In the sensitivity analysis section, each criterion weight was changed from 0 to 1 with step 0.1. Other criteria weights were designated proportional to their original importance to meet the condition of summing to 1. Hashemizadeh et al. proposed a decision model for assessing the renewable energy investment risk in belt and road initiative countries [87]. To perform the results robustness examination, the authors used an approach based on modifying the one at a time criterion weight by 10%, 20%, and 50%. Maliene et al. directed their research to examine the dispersion of relative importance values contributing to the ranking uncertainty based on the practical housing affordability problem [88]. In the first proposed approach of verifying the robustness of the results, the authors model small (5%) and large (50%) changes in criteria weights by increasing and decreasing values with keeping the rest weights unchanged. The second approach identified the most critical criterion based on the smallest relative change in the percentage observed while comparing rankings for subsequent criteria weight changes. Kechagias et al. assessed the supply chain operations with the AHP and PROMETHEE methods [89]. The authors used 10 different scenarios for criteria weighting to analyze the potential differences in results. A similar approach was used by many researchers, for example, by Fuentes and Vervoort, where they used 7 scenarios [90], Pagone et al. with 4 different weights distributions [91], Russo et al. for 24 different weights configurations [92], and Agboola et al. with 9 scenarios for criteria weighting was applied [93].

2.4.2.2. Alternatives values modification.

The second approach that noticeably distinguished itself in terms of the number of applications in the research was the manipulation of data on the values representing the characteristics of the alternatives relative to the criteria in the problem. This approach provides insight into the impact of modifying the values defining decision variants on their attractiveness. In contrast to the first approach, which was most commonly used in the papers included in the review, modeling the values of the alternatives uses the assumption of modifications made within the values in the decision matrix rather than in the values of the criteria weights describing the relevance of the decision criteria in the evaluation process. It is important to indicate that modifying the value of alternatives can represent the effect achieved when negotiating contract terms or choosing product specifications with other parameters, among others. It makes it possible to indicate the order of magnitude that must be achieved for a given decision variant and the values describing it against given criteria to be classified as more or less attractive. In the studies considered in the review, the authors used different approaches to obtain results on the robustness of the results to change. Feizi et al. proposed a framework for assessing multifaceted transportation performance measures for smart cities [94]. Besides examining the impact of changing single criterion weights in

the model results, the authors decided to use a sensitivity analysis with a single performance measure value to check the uncertainty of the quantified value of individual alternatives in each criterion. Humphries Choptiany and Pelot determined an MCDA model integrated with a risk assessment framework for carbon capture and storage [95]. The authors decided to apply the sensitivity analysis considering the modification of the criterion value, indicating that it provides additional knowledge to decision-makers about the robustness of the results to external factors. In the presented approach, each criterion value was modified by ±10% of its mean. Moreover, the Monte Carlo simulation was used to explore the effect of the probability distribution of the criteria values on the overall viability of the alternatives. Maréchal et al. directed their research to Managed Aquifer Recharge (MAR) [96]. To examine the model stability, the authors planned their experiment on the approach using the rate of variation in one factor concerning a variation in another factor. The sensitivity analysis of the levelised cost of the MAR scheme has been computed for all the input parameters. Elavarasan et al. used the MCDA model based on Fuzzy AHP and Fuzzy TOPSIS methods to assess user satisfaction-induced demand-side load management for an industrial building [97]. Two critical criteria factors were identified to which the sensitivity analysis approach using the modification of the alternative values regarding given criteria was performed. The HOMER simulation was used for this purpose. The solar irradiation values ranges were modified from 4.90 to 5.10, and the load demand values varied between 278 and 320. Manikkuwahandi et al. addressed the problem of expansion of the Mahaweli multipurpose reservoir system in Sri Lanka [98]. The MAVT and ELECTRE III methods were used to determine the decision model. The authors applied the sensitivity analysis approach based on examining both attribute performances and decision-makers weights. For this purpose, 1000 Monte Carlo simulation runs were performed by changing the ±20% of attribute performance values and criteria weights. Alinezhad et al. examined the sensitivity analysis of the SAW method [99]. The authors proposed a new approach for sensitivity analysis of MCDA problems based on changing one element of the decision matrix and emphasized that the proposed technique allows for determining changes in the results of a decision problem. The mentioned examples show that different analysis techniques can be used to modify the attribute values and can produce results from which additional knowledge can be extracted to provide a comprehensive view of the problem to the decision-maker. Moreover, it leads to making a more conscious decision, taking into account potential changes caused by the possible uncertainty of the decision variants' characteristics.

2.4.3. Analysis of scientific indicators and connection structure

Based on the articles included in the review, the 20 most-cited papers are presented in Table 1, along with the number of citations of the papers, the methodology used in the study, the sensitivity analysis approach used, the decision problem addressed, the year of publication and the reference to the paper. It is worth noting that more than half of the papers presented in the overview, more specifically, 11 of them, were dedicated to modifying the criteria weights. Two of the most popular studies considered comparing the performance of MCDA methods in a given problem. In turn, 5 studies focused on modifying the parameters of the methods used to assess decision-making variants. In contrast, when analyzing the practical problems addressed, research works were mainly directed at supplier selection, the choice of renewable energy station locations, risk assessments, or business operation quality assessments. It demonstrates the wide range of practical applications of decision-making models using sensitivity analysis research and underlines the popularity and relevance of this research among academic audiences.

To present the connections between the scope of the works considered in the performed review, the VOS Viewer tool was used to generate the graph of connections. The text data was analyzed, taking into account the words from abstracts, keywords, and titles of the works from the reviewed papers. The initial threshold that was set regarding the number of occurrences of the subsequent words equaled 20 occurrences. It resulted in obtaining the network of 79 nodes with 4 individual clusters. However, some nodes identified in the network were general and did not refer to the subject of the research or how the sensitivity analysis research was conducted. To this end, 11 nodes were removed from the network, namely the nodes representing words: time, Turkey, novel, use, term, set, addition, research, work, paper, and data. The generated graph with connections is presented in Fig. 4. It can be seen that the nodes that have the greatest number of connections with others are the ones representing the words: *criterium*, *approach*, *sensitivity analysis*, and *model*. Considering the nodes representing MCDA techniques, the *AHP* and its full name (*Analytic Hierarchy Process*) were identified as the ones with the most references in the reviewed research papers. As the fields of decision problems, the *sustainability*, *supplier*, and *GIS* were identified in the determined network. On the other hand, nodes representing the *criteria weight*, *scenario*, and *evaluation criterium* were visible and had a direct connection to sensitivity analysis approaches based on modifying the criteria importance. Based on the presented graph, it can be seen what nodes played the most important role in the reviewed research papers. Moreover, it should be borne in mind that not all of the nodes were considered, as the initial condition required the minimum number of 20 occurrences in the network. All nodes below this threshold were not included in the visualization. To this end, it is possible to identify the most popular phrases that were used in the works included in the review, based on which the most popular areas of applications and sensitivity analysis approaches can be indicated.

2.5. Risk of bias in studies

It is worth noting that each article selected for review was manually checked to ensure that it met the inclusion criteria. Consequently, in the end, more than 250 of scientific studies on the issue of decision-making with sensitivity analysis were reviewed. Each of the works read was carefully reviewed regarding the sensitivity analysis, the description of its application, and the computational results obtained. It should also be noted that the papers were selected randomly. It translates into the statement that no specific authors, no particular journal, or the number of citations were not influencing the consideration of a given paper in the review. Then, as long as the initial conditions were met, such studies were added to the collection database in the Mendeley reference manager, which was the main tool for item management. Due to the lack of automation and the manual way in which the papers were selected, a marginal bias can be expected to be present in the review. However, maintaining an objective approach and the randomness of the work selection makes this bias minor and does not strongly affect the review results.

2.6. Certainty of evidence

Considering the amount of research available in the area of decision-making using sensitivity analysis, it is impossible to perform an exhaustive review taking into account all published studies. In addition, it must be considered that new research papers are being developed all the time, further increasing the number of papers in this area. Based on this, it was decided to include 250 of research papers in the review in order to present as accurately as possible the distribution and ways in which sensitivity analysis techniques can be applied to examine the robustness of rankings. Only papers meeting the inclusion conditions were considered, limiting the scope to an area directly belonging to the interest of this review. Furthermore, it should be borne in mind that papers meeting the criteria set were then selected randomly, contributing to objectivity and increasing the certainty and impartiality of how papers were included in the review. The percentage distribution of research subjects and techniques used within the sensitivity analysis

Table 1
20 most cited papers considered in the review regarding applying sensitivity analysis in Multi-Criteria decision analysis problems.

Citations	Methodology	Sensitivity analysis approach	Problem	Year	Reference
640	MARCOS	Results comparison for 21 weights scenarios	Sustainable supplier selection in healthcare	2020	[100]
564	TODIM	Modification of θ parameter value in TODIM method	Green supplier selection	2017	[52]
505	Fuzzy TOPSIS	Modification of α parameter value in Entropy method	Renewable energy supply systems	2015	[101]
269	OWA, AHP	Monte Carlo and Global SA for criteria weights	Evaluation of the uncertainty of landslide susceptibility maps	2014	[102]
258	Fuzzy AHP, Fuzzy TOPSIS	Replacing single criterion weights from Fuzzy AHP	Water loss management	2016	[55]
256	Fuzzy ANP, Fuzzy DEMATEL, Fuzzy TOPSIS, Weighted Goal programming	Modification of parameter influencing the objective function	Sustainable-reliable supplier selection	2020	[103]
241	Fuzzy Best–Worst Method, Fuzzy CoCoSo	Modification of p and q parameters influencing the calculation of the weighted sequences of suppliers	Sustainable supplier selection	2020	[104]
232	Fuzzy Best-Worst Method, Fuzzy VIKOR	Modification of θ parameter value, changing criteria weights by ±20% and 30%, the three test criteria of Wang and Triantaphyllou	Determination of failure mode and effects analysis models	2018	[51]
230	Fuzzy TOPSIS	Changing subsequent criteria weights one at a time	Prioritization of renewable energy alternatives	2017	[105]
209	MEREC, ANOM	Changing the number of alternatives and criteria for weights generation	Determination of new objective weighting method	2021	[106]
197	Picture fuzzy normalized projection-based VIKOR	Modification of v parameter value in VIKOR method	The risk evaluation of the construction project	2018	[107]
191	Interval Type-2 Fuzzy TOPSIS, VIKOR	Results comparison for six criteria weights scenarios	Assessment of fintech investments in European banks	2021	[108]
179	AHP	Changing subsequent criterion weights one at a time	Modeling the flood susceptibility mapping of arid areas	2020	[109]
172	ANP	Changing subsequent criterion weights one at a time	Renewable energy policy planning	2020	[110]
171	AHP, PROMETHEE II	Changing subsequent criterion weights by ±10%, 20% and 30%	Selection of location for sustainable offshore wind energy stations	2021	[111]
171	CRITIC, Pythagorean Fuzzy CoCoSo	Results comparison for different criteria weighting methods	Evaluation of 5G industry	2020	[112]
169	FUCOM, MARCOS	Comparison of different MCDA methods	Evaluation of Human Resources in a Transport Company	2020	[113]
166	SAW, MOORA, VIKOR, COPRAS, CODAS, TOPSIS, D'IDEAL, MABAC, PROMETHEE, ORESTE	Comparison of different MCDA methods	Selection of location for logistical center	2018	[114]
154	Fuzzy AHP, Fuzzy TOPSIS	Results comparison for different criteria weights scenarios	Green supplier selection in the Industry 4.0 era	2021	[115]
146	Fuzzy DEMATEL	Results comparison by changing the input of cluster weights	Evaluation of sites for ecotourism development	2016	[116]

shown in Fig. 3 respectively on (A) and (B) should therefore be treated with some degree of probability because of the impossibility of taking an exhaustive approach and considering all available research in this area. However, it should also be emphasized that the set of applied research tools and methodologies used in developing the following literature review contributes to its structured design and how it was undertaken. The PRISMA methodology has influenced the use of a framework according to which the subsequent stages of the review should take place, as well as emphasizing where specific attention should be paid when conducting the research and describing the results. It contributes to increased confidence in the results obtained than if such a review had been performed without a clearly defined methodological framework.

3. Sensitivity analysis classification

Based on the performed review, it was possible to identify the core classification of the sensitivity analysis approaches used in the research works directed to multi-criteria decision analysis problems. The proposed classification was presented in Fig. 5. The main categories were identified, and the selection process regarding various scientific purposes was presented. In order to indicate how the specific category of sensitivity analysis approach influences the results obtained through the calculation process and how they can contribute to determining the results' robustness, the identified categories are described below.

3.1. Category 1 – Approach

When planning an experiment to measure the robustness of the results of a multi-criteria analysis to change, different approaches can be used on how to examine changes in the input parameters. The generation of data that determines potential changes in the model's input information can be performed randomly. Then we are dealing with a probabilistic approach. This approach is characterized by multiple repetitions of the data generation process, which are applied throughout the decision-making process. It reflects a certain randomness that can occur in the problem, where each iteration of the study represents the possibility of a new set of data and potential evaluation conditions. The results obtained with this approach allow for determining how the data's randomness affects the attractiveness of the proposed solutions. The multiple repetitions of the computational process make it possible to indicate with what probability a particular outcome resulting from the study is possible. Using this approach, it is possible to verify how the randomness appearing in the problem affects

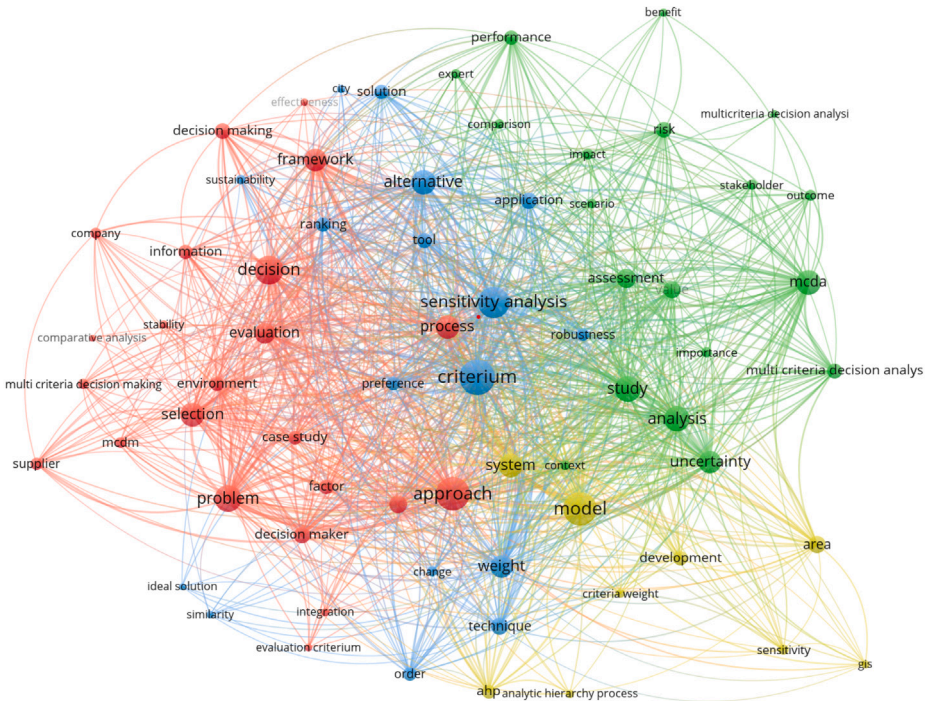

Fig. 4. Graph of connections from the keywords, titles, and abstracts of the works from the review with at least 20 occurrences.

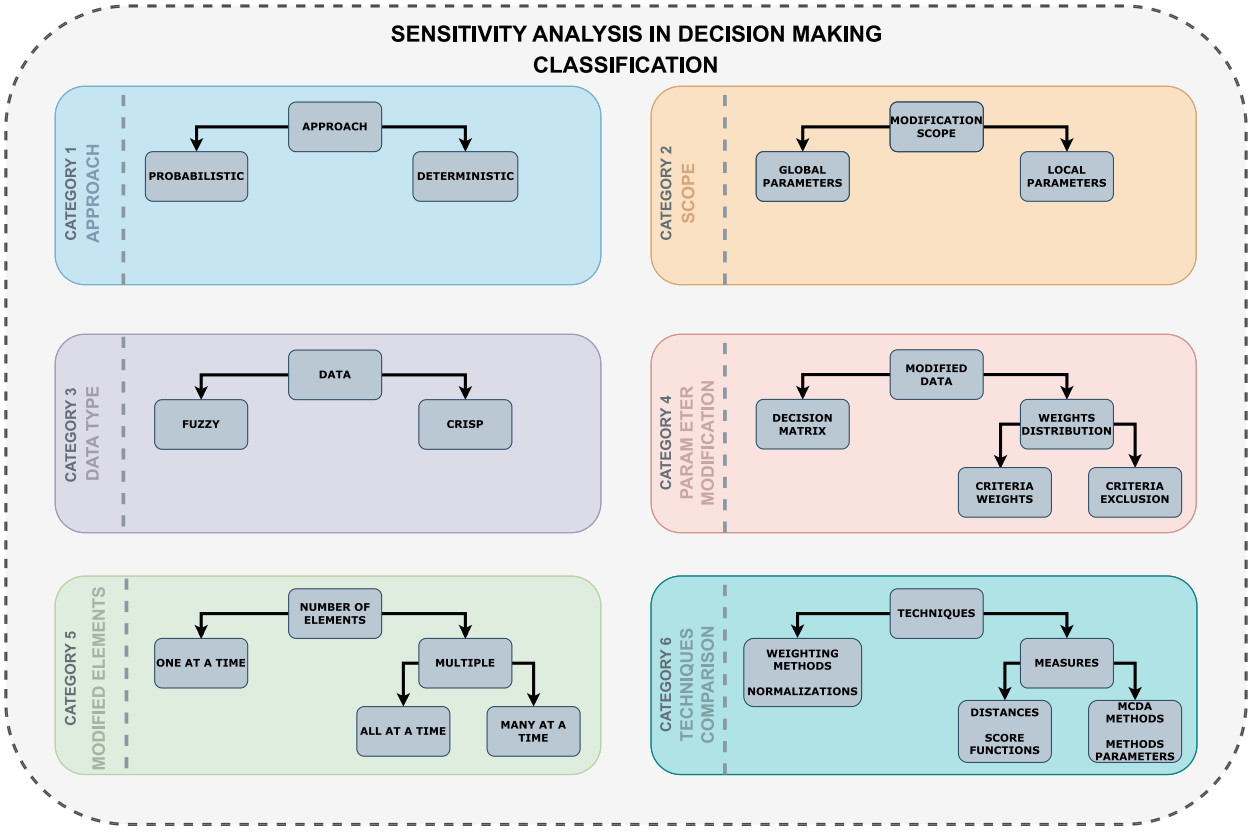

Fig. 5. Classification of sensitivity analysis approaches in Multi-Criteria Decision Making.

potential changes in the results. Within the probabilistic sensitivity analysis approach in decision-making, techniques such as Monte Carlo simulation, variance-based analysis, and Bayesian approach, among others, can be used.

In contrast, if the study is based on a previously developed approach to changing the input data and not including randomness in the process, approaches based on deterministic value change can be used. In contrast to the probabilistic approach, the expert conducting the analysis must identify a specific set of values to be used to modify the input data. The developed combinations of data sets are then used in a computational process from which the final results are obtained. Comparing these with the reference values obtained before the modifications indicates which combination of parameter values produced the respective results and how they differ from the initial outcome. In a deterministic change approach, the expert decides how to model the changes in the data and is thus able to determine the impact of specific values on the results obtained. In addition, it allows for systematic, structured, and repetitive testing leading to uniform results, whereas the probabilistic approach is based on randomness and probability of given values from a given data set.

3.2. Category 2 – Scope

Classification of approaches to performing sensitivity analysis can be made according to the scope of the changes carried out. In the literature, two main categories can be found regarding the scope of data changes in studies incorporating sensitivity analysis in a multi-criteria approach, namely global and local range. The first is based on the consideration of all main parameters taken into account in the decision problem. It means that each factor considered in the multi-criteria problem is analyzed in the context of the impact of a change in its value on the results obtained. It ensures a holistic approach to the problem posed and an understanding of the impact of potential changes in each parameter on the results. On the other hand, a local approach should be applied if the study focuses only on selected elements that also represent sub-level parameters in the problem. It takes into account the modification of only a specific group of factors so that the other parameter values remain constant. By definition, the local identification of parameters should limit the factors to modifiable elements that can actually be changed. In this approach, it is assumed that the expert can identify which factors should be tested for modification of their values. If, on the other hand, the expert is not equipped with such knowledge or is uncertain which factors should be examined, then a global approach can be taken, which allows subsequent elements in the problem to be examined.

3.3. Category 3 – Data type

Multi-criteria calculations are performed in two main areas conditioned by the uncertainties arising in the decision problems. When the data are known precisely, multi-criteria evaluations are performed on the crisp numbers. On the other hand, when uncertainties occur in the problem, different extensions of fuzzy sets are used to represent the uncertain data. Based on these two identified areas, it is also possible to classify the approaches used in multi-criteria calculations that take into account the sensitivity analysis of the results. For complete data, a crisp data modeling approach is used. In contrast, with possible uncertainties and missing data in the problem, a fuzzy approach is applied.

Both ways of modeling data in multi-criteria problems are based on the assumption of exploring the impact of changing parameter values on the resulting differences in outcomes. In addition, observing the differences that emerge makes it possible to study the robustness of the model to potential changes and to identify cases in which selected decision variants may prove more attractive relative to others. It should be mentioned that, regardless of how the data are represented, similar findings can be achieved in terms of determining the robustness of the results. Available sensitivity analysis techniques support both one area and the other so that the robustness of the proposed results of multi-criteria models can be effectively examined. It does not change the fact that it is important to distinguish which type of data a sensitivity analysis study is to be performed, as this will influence the selection of appropriate techniques for this purpose.

3.4. Category 4 – Parameter modification

An area where the expert can modify the conditions for exploring the robustness of decision models to changes in input values is in determining the parameters to be changed. It is important that the objectives of the study are well identified so that an appropriate approach can be selected and a sensitivity analysis technique that fits the purpose can be chosen. When the expert wants to study the impact of changing the values of the attributes that describe the decision variants, an approach that takes into account the modification of the values contained in the decision matrix defined for the multi-criteria problem should be chosen. This approach allows modifications to be made to the values that characterize the alternatives under analysis so that it is possible to indicate how a potential change in the values of the selected criteria affects the attractiveness of that decision option. It also allows the modeling of possible input variants and makes it possible to indicate the magnitude of changes that allow the attractiveness of a given alternative to be increased or decreased.

When the values describing the characteristics of the decision variants included in the decision matrix are to remain constant, an approach to modifications associated with the identified criteria affecting the evaluation can be used. In this situation, an expert seeking to model changes in the inputs to the problem being solved has a choice of two approaches that reflect modifications to the values associated with the criteria. The first concerns the modification of the values of the weights assigned to each criterion. This process allows the relationship between the importance of a particular parameter and the attractiveness of the decision options under consideration to be explored. The approach of changing the values in the vector of criteria weights allows the representation of the different relevance of these elements in the problem so that it is possible to determine how the defined model will respond to changes in evaluation preferences.

The other possible approach to modifications related to the set of criteria in the problem is to use the mechanism of excluding selected factors from the multi-criteria evaluation. It involves modifying the decision matrix in a way that the columns in the matrix corresponding to the criteria excluded from the problem are also omitted when performing the calculations. By doing so, it is possible to identify the importance of each criterion in the problem and how significantly they may affect the differences in the proposed results. The exclusion of the indicated criteria from the problem allows the modeling of the intention to omit a given evaluation factor. Additionally, it indicates the resulting relationships between the criteria concerning the assessment obtained from the multi-criteria model.

3.5. Category 5 – Modified elements

Investigating the robustness of multi-criteria analysis results to change can also be divided by the number of elements to be modified. The available approaches allow modeling changes of one or more parameters in the problem simultaneously so that the expert can select the number of parameters and indicate the specific elements to be modified in a deterministic and planned manner. For approaches based on modifying the values of single elements, One At a Time (OAT) techniques should be used. They are also encountered under another designation, namely One Factor At a Time (OFAT). The two terms can be used interchangeably and refer to situations in which a single parameter from the decision problem selected by the expert is modified. Such a process of examining the impact of changes to a

single parameter can be repeated many times, taking into account the modification of further parameters indicated in the problem so that the potential results and attractiveness of decision options with planned modifications can be known.

The OAT approach assumes the modification of a single parameter in a single study. If the expert considers the possibility of modifying the values of multiple factors, other techniques should be used to select the set of parameters to be changed. If the study is to include modifications to the values of all factors in the problem simultaneously, the All At a Time (AAT) approach should be used. On the other hand, if the values of only a selected set of parameters are to be modified, then the Many At a Time (MAT) approach should be followed. The latter approach allows flexibility in determining the parameter sets to be modified, allowing the expert to prepare a study based on multiple defined sets. It allows the potential results and the impact of changes in parameter values from individual sets on the evaluation of decision variants to be known.

3.6. Category 6 – Techniques comparison

Due to the availability of multiple techniques developed in multi-criteria decision-making, different ones can be used to design decision-making models. These techniques are developed based on distinct assumptions and mathematical transformations, and as a result, their results can vary significantly. It poses a problem and a challenge for experts in selecting these techniques so that the results obtained are reliable. Based on the availability of many approaches that can be used in multi-criteria modeling, it is possible to identify different approaches to study the sensitivity analysis of the proposed results.

When planning a study of the robustness of the results to change and aiming to examine the impact of different techniques that modify the input data in a decision problem, different approaches can be used to determine the criteria weights and to normalize the data. The first-mentioned approach based on weighting methods allows the selection of a set of methods determining the weights using a different approach. It allows the model's results to be determined according to the different importance of each criterion in the problem. The results obtained can then be compared with each other to note potential differences arising from the different scenarios. At the expert's disposal, various methods are available to determine weights objectively (Equal, Entropy, Criteria Importance Through Intercriteria Correlation (CRITIC), and Integrated Determination of Objective Criteria Weight (IDOCRIW), among others) and subjectively (for example, Analytical Hierarchy Process (AHP), Ranking Comparison (RANCOM), Full Consistency Method (FUCOM), and Kemeny Median Indicator Ranks Accordance (KEMIRA)). In the case of normalization, the expert can select the technique that will be used to standardize the data in the decision matrix at the beginning of the model calculation. Due to the existence of different normalization techniques and the apparent differences between their effects on the results obtained, this choice has an important impact on the proposed results. Approaches such as Sum, Min–Max, Vector, Linear, or Max normalizations, among others, can be used to perform data normalization.

When a sensitivity analysis aims to include the robustness of the results to changes in the metrics used within individual MCDA methods, then two groups of techniques can be used to change the approach when calculating the result. One is distance metrics, which are used in many methods to quantify the differences between given decision variants. An expert can plan to explore the stability of the results to changes in the metrics used in the methods' procedures and then compare the results and determine whether these changes affect the proposed rankings. Metrics such as Euclidean distance, Hamming distance, or Vertex distance, among others, can be used. On the other hand, the second group of techniques are metrics that allow the calculation of crisp values from fuzzy numbers. They are only applicable to Fuzzy MCDA methods, which use data in the form of fuzzy sets in the calculations and then convert these values to crisp numbers when calculating the final result. There are also significant differences in the performance of Fuzzy MCDA methods in combination with different score functions, so their selection also directly impacts the results of the decision-making analysis. In the uncertain environment based on Triangular Fuzzy Numbers (TFNs), one can choose from techniques such as Mean, Mean area, or Weighted mean defuzzification methods. In the Intuitionistic Fuzzy Numbers (IFS) domain, on the other hand, methods such as Chen, Kharal, Thakur, or Wei score, for example, are available.

An expert planning a sensitivity analysis study of multi-criteria models can use two more approaches that do not modify the values of the input data and do not change the type of metrics used in the calculation using MCDA methods. One such approach is to modify parameters specific to selected methods from the MCDA field. One such method is the VIKOR method, which uses the υ parameter. Its value determines how the preferences are calculated in the final phase of the calculation. By default, the value of this parameter is proposed to be set to 0.5. However, it is fully adjustable, and changing this value directly impacts the results obtained. Another technique that relies on an explicitly indicated value for method parameters is, for example, the TODIM method, whose calculations are based on the value of the θ parameter. It is possible to perform a study in which the value of the method parameter is modified, and the impact of the change in this quantity is observed in the results of the decision model. Another robustness investigation variant is using multiple MCDA methods for the indicated decision problem. Due to the differences that occur in the assumptions of these methods and the different approaches to the transformations performed in the subsequent computational steps, the results of these methods may differ significantly. It makes it difficult to indicate which MCDA method should be used for a given problem. Therefore, it is possible to use multiple techniques to solve a single problem to see if different selection preferences emerge and how strongly they differ. Methods such as Additive Ratio Assessment (ARAS), Evaluation based on Distance from Average Solution (EDAS), Complex Proportional Assessment (COPRAS), Characteristic Objects Method (COMET), Stable Preference Ordering Towards Ideal Solution (SPOTIS), or Technique for the Order of Prioritization by Similarity to Ideal Solution (TOPSIS), among others, are available to the expert. Selecting a set of methods and solving a given problem using them can indicate which solution is the most preferred choice. In addition, it should be mentioned that by applying different approaches to the calculation, multiple result vectors are obtained. It, in turn, allows the use of methods to determine compromise rankings so that a common ranking is produced, taking into account the results from the different methods.

Based on the identified categories of segmentation of approaches to conduct sensitivity analysis in decision problems, the expert can identify the areas that should be included in the study. Using the classification indicated in the flowchart in Fig. 5, the selection of techniques and approaches for conducting sensitivity analysis of decision model solutions can be made in a structured and schematic manner. In addition, based on this, the expert can make a more conscious choice as to how to test the robustness of the results to change due to the ability to compare the available approaches and select a dedicated solution to the decision problem posed.

Undertaking a review of research work dedicated to decision-making problems with sensitivity analysis has identified the most popular approaches used in this area. These are presented in Table 2, where five approaches classified according to the categories shown in the diagram in Fig. 5 are included. It can be seen that in certain areas, not all categories have techniques indicated that correspond to the sensitivity analysis approach used for the results. It is dictated by the fact that some approaches are mutually exclusive, so selecting a technique from a category will exclude the possibility of selecting a technique from another category. In Table 2, this occurs in the case

Table 2
Identified classes of the most popular sensitivity analysis approaches in Multi-Criteria Decision Analysis.

Class	Categories					
	1	2	3	4	5	6
1	Probabilistic	Global	Crisp	Decision matrix	–	–
2	Probabilistic	Global/Local[a]	Crisp/Fuzzy[a]	Criteria weights	–	–
3	Deterministic	Global	Crisp	Criteria weights	One at a time	Weighting methods
4	Deterministic	–	Crisp/Fuzzy[a]	–	–	MCDA methods
5	Deterministic	Global	Crisp/Fuzzy[a]	Decision matrix	–	Normalizations

[a] Indicates that two of the listed approaches can be used interchangeably.

of classes based on the probabilistic approach, where the selection of this technique prevents the selection of techniques from category 6 on techniques comparison from being determined. In contrast, in the case of class 4, where a deterministic approach to MCDA method comparison is identified, the selection of elements in category 4 on parameter modification or in category 5 on modified elements cannot be specified. Notably, the identified classes mostly focus on modifications concerning the values of the criteria weights. Two of the approaches also allow manipulation of the decision matrix data. In addition, most approaches allow for the interchangeable use of crisp and fuzzy data. From the classes shown, it can be seen that current sensitivity analysis approaches focus on the limited and selected issues of examining the robustness of rankings, thus leaving the opportunity to develop new methodologies for this purpose.

4. Review of sensitivity analysis frameworks

The important additional information that can be indicated from the sensitivity analysis of the results obtained from the MCDA models constitutes to developing frameworks directed towards presenting the methodological approaches that can be applied to examine the robustness of the outcomes. Based on the proposed steps of conducting the sensitivity analysis of the results from the multi-criteria assessment, it is possible to extract additional knowledge about the robustness and possible outcomes that can be achieved with different initial conditions. Moreover, the developed frameworks aim to determine a structured approach for examining the sensitivity of the results and focus on different objectives of sensitivity analysis that can help to test different areas of multi-criteria models' performance. Based on frameworks presented in the literature, selected methodologies were shown in Table 3, where the objective of the sensitivity analysis, year of publication, the author, and reference to the research paper are presented. The frameworks that were presented in Table 3 were selected based on the availability of the formal notation and description of proposed approaches and the verification of the determined sensitivity analysis techniques in the practical decision problems. Moreover, the research papers with determined methodologies were selected based on the proposition of applying the sensitivity analysis techniques to multi-criteria problems in general. It translates into not considering the frameworks that aimed to operate only in specific conditions such as spatial multi-criteria decision-making [117], healthcare multi-criteria decision-making [118], and any other specifically directed and domain approaches.

It can be seen that the available frameworks to conduct the sensitivity analysis of the results obtained from the multi-criteria evaluation take into account various objectives aiming to examine the robustness of the results differently. Furthermore, it should be pointed out that there are two main areas of operation to which the presented frameworks are directed. These areas cover modifying the criteria weights to identify the most important and most sensitive criteria in the decision problem and the modification of values of elements in the decision matrix to identify the degree of reliability and the most vulnerable parameter that can cause changes in the assessment. Moreover, it can be seen that these areas correspond to the application approaches of sensitivity analysis identified in the review and shown in Fig. 3(B). To present the main assumptions of the selected frameworks for sensitivity analysis in decision-making, three of the methodologies presented in Table 3 are described.

The frameworks selected for the detailed description were chosen based on their approaches for undertaking the sensitivity analysis assessment in multi-criteria problems. It aimed to present frameworks with different assumptions and various techniques that can be used for the sensitivity analysis examination. Furthermore, it allowed to provide descriptions of multiple approaches that can be used for this purpose and show the readers how the robustness of the results could be determined based on different techniques. Each of the selected frameworks described in detail proposed three different approaches for conducting the sensitivity analysis in multi-criteria problems, which resulted in nine presented approaches.

4.1. Wolters and mareschal methodology

The first overview of the proposed approach for sensitivity analysis in decision-making considers the framework presented by Wolters and Mareschal in 1995 [123]. The authors proposed an approach to performing sensitivity analysis of multi-criteria decision-making based on three distinct techniques. To examine the robustness of the results, the framework presents:

- an approach for assessing the sensitivity of a ranking to changes in the evaluations of all alternatives regarding given criteria
- an approach for indicating the influence of changes in given criterion scores of an alternative, which represents modifications in a decision matrix
- an approach for indicating the minimum modification of the weights required to promote an alternative to 1st position in the ranking

The authors emphasized that the first two approaches aim to enable using the MCDA evaluation in dynamic circumstances, while the third approach is characterized as a measure to analyze the total space of criteria weights. In the first presented approach, the authors modeled the potential changes in two selected criteria with the previously defined six threshold values representing the potential increase of values describing the alternatives. After this, based on the selected criteria and thresholds, the values in the decision matrix for all decision variants and those two specific criteria were modified by increasing values in columns simultaneously. Having six threshold values, the authors obtained six different decision matrices with changed values in two selected columns representing the given criteria. These matrices were then used to perform the multi-criteria evaluation based on which the rankings were established. Through this approach, the authors aimed to indicate how the potential evaluation scores could vary in time based on the modeled threshold values corresponding to potential changes in values characterizing the decision variants. To apply this technique in the analysis of the robustness of the results, the possible changes in values should be known to identify the thresholds.

The second presented approach concerns modifying criteria values for a selected alternative. The authors selected 4 alternatives for which the value changes for 3 criteria were performed. The goal was to use

Table 3
Selected frameworks for performing sensitivity analysis of the results obtained from MCDA models.

Sensitivity analysis objective	Year	Author	Reference
Identify the most critical criterion and the most critical value in the decision matrix	1997	Triantaphyllou, E., Sánchez, A.	[119]
Examine the solution stability to changes in criteria weights, Results consistency based on the change of the measurement scale, Results consistency based on the changes of the criterion formulation	2017	Pamučar, D., Božanić, D., Ranđelović, A.	[68]
Identify the potentially optimal alternative based on the distance analysis indicating the dominance of decision variants	2001	Proll, LG., Salhi, A., Rios Insua, D.	[120]
Identify how to model the uncertainty of model input factors and criteria weights	1999	Saltelli, A., Tarantola, S., Chan, K.	[17]
Examine the sensitivity to the Rank Reversal phenomenon with linear transformation of objectives, reciprocal objective reformulation, and removal of alternatives	2023	Nabavi, SR., Wang, Z., Rangaiah, GP.	[121]
Select a group of MCDA methods that guarantees the most robust outcome	2017	Haddad, M.	[122]
Examine the degree of the reliability of the decision matrix elements based on the estimation of the value error	2018	Mukhametzyanov, I., Pamučar, D.	[114]
Determine the sensitivity of rankings to changes in the evaluation of alternatives on certain criteria, The influence of specific changes in given criteria scores of alternatives, The threshold value of criteria weights changes to promote an alternative to 1st position	1995	Wolters, W.T.M., Mareschal, B.	[123]
Identify the most critical criterion for which the smallest relative change in weights value alters the ranking, Determine independently the effect of each criterion to MCDA outcome	2018	Maliene, V., Dixon-Gough, R., Malys, N.	[88]

the iterations to increase the scale of changes in the decision variants and obtain the 1st position for the tested alternative. The authors indicated that the values in the decision matrix were reduced for one criterion. However, the authors only mentioned correcting the values of two other criteria and did not show how the specific modifications were performed. The results were presented as the interval range for subsequently tested scenarios and aimed to indicate the range of changes for a specific criterion that guarantees the given alternative a 1st place in the ranking. The presented technique can be applied to problems in which the selected decision variants have different parameters characteristic regarding the varied input conditions. Moreover, the criteria in this approach should be selected carefully, as only factors for which the corresponding values in the decision matrix can change should be considered.

The last proposed approach for conducting the sensitivity analysis in the decision-making problem concerns indicating the minimum modification of criteria weights to guarantee the specific decision variant 1st place in the ranking. For this purpose, the authors proposed the application of Linear Programming (LP) with different constraints that were used in varied combinations to create different test scenarios. Based on the obtained results, it was concluded that for the high-ranked alternatives, the determined threshold of weights value to change would be low. On the contrary, with the lower position of the alternative in the ranking, the indicated criteria weight value to change would be more significant. Moreover, Wolters and Mareschal integrated the presented approaches into the PROMETHEE II method, which allowed them to perform a sensitivity analysis during the decision process. In the research conclusions, the authors indicated that applying the proposed sensitivity analysis framework allows for determining whether an alternative can be reasonably selected considering the specific criteria weights requirements given by the decision-maker.

4.2. Pamučar, Božanić, and Ranđelović methodology

The second presented framework for examining the sensitivity analysis of decision models' results was presented by Pamučar, Božanić, and Ranđelović [68]. The TOPSIS, COPRAS, VIKOR, and ELECTRE methods were selected to examine the proposed sensitivity analysis approaches. In their research, the authors group the decision process into two phases. The first phase considered the application of the MCDA methods, while the second was identified as the examination of the consistency analysis of the used methods. The main goal of the presented approaches was to indicate the MCDA method that keeps the majority of priorities in scenarios during the change of weight values and keeps the rankings stable in case of a change of the measurement scale and criteria formulation way. As the main techniques that should be used to evaluate the results consistency, the authors pointed out:

- an evaluation of solution stability according to changes in weight of criteria
- an assessment of the consistency of the results based on the change of the measurement scale for qualitative criteria
- an evaluation of the consistency of the results based on the change of the criterion formulation way

As the first proposed approach, the MCDA methods were examined regarding their stability, and for this purpose, the criteria weight changes technique was indicated. Its objective is to determine how changes in criteria weight lead to differences in the obtained rankings. The authors indicated that this type of analysis could be used to confirm rankings determined through mathematical models and to select the optimal choice. However, they emphasized that modifying relying only on the criteria weights is not enough to provide conclusions about the reliability of the results. The authors supplemented the first approach with two additional techniques to propose a comprehensive

approach that ensures the stability of decision models. The evaluation of measurement scale changes was indicated as one of the additional sensitivity analysis techniques. As the main assumption, the Measurement Scale Independence (MSI) condition was formulated to indicate the so-called independence of the value scale condition. To measure cardinal values on different measurement scales, the positive affine transformation represented as $v_{ij}^{+} = av_{ij} + b$ is presented, where a and b are constants under the condition of $a > 0$. The authors emphasized that the results obtained through the MCDA methods have to be the same for different measurement scales. It should translate into a unique assessment outcome when in a decision problem, for example, the length is presented as meters, kilometers, or miles. The evaluation scores should also be the same when qualitative attributes are measured on the $1, 2, 3, 4, 5$ scale or its positive affine transformation $y = 2x - 1$, which produces the $1, 3, 5, 7, 9$ scale.

As the last of the proposed approach for analyzing the stability and consistency of the MCDA results, the authors focused on the criteria formulation way and changes in its definition. The Criteria Formulation Independence (CFI) condition was determined as a requirement for the choice rationality of an individual decision-maker. It covers the problem of formulating criteria in different ways and indicates that normatively equivalent formulations should not affect the individual preferences of experts. In the decision-making process, it refers to changing the criteria types to opposite types, reversing its objective direction (from cost to benefit type, and from benefit to cost type). As the decision made by the expert in the judgment process should be consistent, despite changing the criteria formulation manner, the authors indicated that the MCDA methods should satisfy the same condition as they are applied to reflect the expert behavior. As a practical problem, the selection of the logistical center location was used. Based on the performed experiments, the authors indicated that three of the four applied methods did not provide reliable results, namely the COPRAS, TOPSIS, and ELECTRE methods. However, they also addressed that this conclusion is drawn specifically for the used decision problem and cannot be generalized. Moreover, they emphasized that the MCDA methods are just tools to support decision-makers in the decision process, proposing the most rational choices to them. The decision-maker should make the final decision considering his/her personal preferences.

4.3. Nabavi, Wang, and Rangaiah methodology

The last described sensitivity analysis framework was proposed by Nabavi, Wang, and Rangaiah [121]. The authors focused on establishing the methodology that can be used to examine the sensitivity of the results to the Rank Reversal (RR) phenomenon, which is a common and undesired outcome visible in multiple MCDA methods. For this purpose, changes in the decision or objective matrix (DOM) are assessed with 3 types of modifications:

- linear transformation of an objective (LTO)
- reciprocal objective reformulation (ROR)
- removal of alternatives (RA)

After performing the presented approaches for sensitivity analysis modifications, the authors proposed to examine the results in three aspects, namely the assess the effect on the recommended alternative, the effect on the 3 top-ranked alternatives, and the effect on the ranking of all alternatives, using, for example, the Spearman's rank correlation coefficient. The proposed framework aims to provide insights and recommendations on relatively more robust MCDA methods for different types of applications, translating into the possibility of making more informed and conscious decisions.

The Linear Transformation of an Objective (LTO) assumption refers to the concept of Independence of the Value Scale (IVS) or the Criteria Formulation Independence (CFI) presented by Pamučar et al. in [68]. Nabavi, Wang, and Rangaiah also emphasized that this factor is important in determining the final ranking, and changes provided in the criteria formulation should not affect the relative order of alternatives. In the study, the authors used the linear transformation ($y = 3x + 4$) to determine the values of objectives. The Reciprocal Objective Reformulation (ROR) reflects the manner of determining the direction of objectives for subsequent criteria in the decision problem. As the criteria types can be established as profit for values maximization and cost for values minimization, the ROR assumes that a particular objective can be reformulated equivalently. Based on this, for a profit criterion type, it can be determined as minimization of 1/profit or constant — profit, and still, the rankings should remain the same. Taking this into account, the objectives presented as the smaller-the-better or larger-the-better form should not influence the decision making process. Moreover, the authors indicated that LTO and ROR should be applied before the data from the decision matrix is normalized.

The Removal of Alternatives (RA) refers to the factor that has a direct impact on reversing the order of alternatives in the ranking. It represents the situation in which the given decision variants are removed from the decision matrix, making them no longer considered in the decision process. This change should not alter the positional ranking obtained from the MCDA methods. However, the Rank Reversal paradox phenomenon is a common problem in many multi-criteria techniques. The authors indicated that the reason for this issue is caused by relying on Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) in the evaluation process in selected methods. To this end, the authors proposed to verify selected MCDA methods with a structured approach for performing modifications in the decision matrix. The first approach considered removing all top-ranked alternatives from the dataset. Then, the remaining decision variants should be shuffled, and based on that, 10% of alternatives placed on top of the ranking should be removed. In the case of floating point numbers representing 10% of the number of alternatives, this number should be rounded to the nearest integer. The authors indicated the main advantages of excluding top-ranked decision variants as it will noticeably affect the assessment of the given methods as different methods can have various top-ranked alternatives. Moreover, they emphasized that when removing some lowest-ranked decision variants in the small set of alternatives it will consider only a few options, which limits the possibilities of being randomly removed after the shuffle process.

The authors verified the proposed framework for sensitivity analysis of the results obtained using the multi-criteria decision-making techniques with 8 common and recent MCDA methods and utilized them for 16 application problems. The Combinative Distance-Based Assessment (CODAS), COPRAS, Gray Relational Analysis (GRA), Multi-Attributive Border Approximation Area Comparison (MABAC), Multi-Objective Optimization Method by Ratio Analysis (MOORA), Preference Ranking on the Basis of Ideal-Average Distance (PROBID), SAW, and TOPSIS methods were used. Twelve of the sixteen problems were classified as a Small Set of less than 20 Alternatives (SSA), and four were marked as a Large Set of more than 50 Alternatives (LSA). Moreover, each decision problem considered from 5 to 13 criteria. The authors concluded that some weighting methods used in the decision-making process are more sensitive to LTO, ROR, and RA. Moreover, the RA had a greater effect on a small set of alternatives than in the case of a large set of alternatives. Furthermore, the authors emphasized that the ROR had the greatest effect on the ranking of alternatives for small and large sets of decision variants despite using different weighting methods. It is indicated that performing the sensitivity analysis based on the proposed approach enables the decision-makers to make more informed decisions.

5. Discussion

A review of works related to the area of decision-making using sensitivity analysis has shown that different approaches are used to test

the robustness of rankings determined by the performance of MCDA methods. According to the identification of the main practical areas in which decision-making models using sensitivity analysis are applied, it can be indicated that the most frequently addressed problems are those related to sustainability, healthcare, and Geographic Information Systems aimed at selecting the most attractive locations. However, these are only the main practical areas identified from the work in the review, and it should be taken into account that decision support systems based on sensitivity analysis are used in many other areas of decision-making. Due to the popularity of techniques in the examination of sensitivity analysis of results, a significant dominance of approaches based on the manipulation of values in a vector of criteria weights has been noted. Modeling changes in the values of the criteria weights can be performed in a number of ways, as the review has shown. However, it should be pointed out that sensitivity analysis studies in many works were based solely on determining the impact of changes in the values of the criteria weights on the rankings, which is only a superficial approach and does not allow for an in-depth analysis of the robustness of the results to changing initial conditions. It raises challenges in terms of identifying how to conduct research on sensitivity analysis of results in the area of decision-making so that the analyses made are more valuable and comprehensive.

From the approaches examined, it is possible to identify areas of activity that represent challenges when using sensitivity analysis in multi-criteria decision-making. One of the main challenges noted in the review study is the lack of an extensive approach to sensitivity analysis of rankings and the limitation to one selected area of testing the robustness of results. Most of the work showed that the research was focused on determining the impact of changes in the values of the criteria weights on the resulting rankings. It is an approach that allows the potential rankings to be explored as a consequence of the changing relevance of individual criteria. This situation can model changes in the decision-maker's preferences or a change in prioritization in the search for the most desirable solution. However, it is a superficial examination and does not explore many aspects in which significant changes may also affect the results. A review of proposed research methodologies indicating approaches to the study of sensitivity analysis has addressed several different techniques that can be applied within the study of the robustness of rankings to change. One such area, neglected in many works, is the modeling of potential changes in the area of the decision matrix, which quantifies the specifics of the decision variants. Making changes to the decision matrix is important because often, the measurements made to obtain a value for a criterion are affected by some measurement error, so the data representation in the decision problem itself can already affect significant discrepancies between the calculations and the actual state of the matter. In addition, modeling changes in the decision matrix makes it possible to indicate the magnitude of potential changes necessary to improve the ranking position, thus determining values that the decision-maker can use to his/her advantage in negotiation processes or in the selection of individual parameters of a given decision alternative.

Another area that is inadequately addressed when examining the robustness of rankings to changes in decision-making is the lack of consideration of differences in performance between selected MCDA methods. As many studies have shown in benchmarking the performance of selected multi-criteria methods, the results can vary significantly between individual techniques in a single decision problem. It, in turn, translates into proposing differing rankings that determine the most preferred choice of decision variant. However, assuming the initial data are the same, a single and unique most preferred solution to a given problem is expected. It can cause problems in selecting the appropriate multi-criteria method to solve a given problem, as using two different techniques may result in two different alternatives being indicated as the most rational choice. It leads to the need to compare the performance of these methods and not base analyses on a single method, as the result may differ for another technique. Based on the use of multiple MCDA techniques in a given decision problem, methods can be used to indicate a compromise ranking that takes into account potential differences in rankings from multiple methods. It indicates the most rational choice based on the consensus ranking of alternatives by multiple methods, so the proposed compromise ranking can be assumed to be more reliable than the ranking derived from evaluating a single MCDA method. Another important aspect in selecting techniques for multi-criteria evaluation is to be aware that these methods rely on multiple metrics, such as distance measures or normalization techniques. Research carried out in comparing the results of individual MCDA methods using different metrics in the calculation process shows that this factor should also be considered in the design of decision-making models, as there are visible differences between the results obtained using different distance measures or normalization techniques. Investigating the robustness of the rankings given the different metrics used in MCDA methods may prove to be as important in the study as investigating different scenarios for criteria weights, as both areas of examination can significantly affect the order of the alternatives in the final ranking. In contrast, many papers ignore the determination of the effect of using different metrics in individual MCDA methods on the final outcome. On the other hand, when comparing selected MCDA methods and attempting to solve a given decision problem using them, exploring all possible combinations of MCDA methods combined with metrics can be time-consuming and result in many combinations to be tested. It results in a challenge to confront and define a sensitivity analysis research approach to effectively test the differences in performance of different MCDA methods in combination with the selected metrics.

An important element in conducting research on sensitivity analysis and the results obtained is how the related experiments are carried out. To obtain reliable and comparable results, it would be reasonable to use the same tools for testing the robustness of the rankings. However, there is a lack of universal solutions in this area, which would allow the free and standardized use of available techniques to study the sensitivity of rankings to changes in multi-criteria decision-making. It creates a research gap that needs to be filled to provide uniform and comprehensive tools for the academic community solving decision-making problems. Additionally, there is a lack of standardized coefficients for determining the degree of sensitivity of solutions, so many results are calculated using different mathematical formulas presented in different forms or units. It causes problems in comparing the robustness of the rankings to one another. A similar problem arises when defining sensitivity analysis research approaches, where different naming conventions are used even for techniques that describe the same research approach. It is visible in the frameworks for sensitivity analysis discussed in Section 4, where Pamučar et al. and Nabavi et al. use two different labels for an indicator describing the independent formulation of criteria. In this case, the names Independence of the Value Scale (IVS) or the Criteria Formulation Independence (CFI) refer to the same indicator, which can cause difficulties in correctly interpreting and identifying approaches. In addition, it can contribute to problems in identifying techniques for sensitivity analysis and problems in selecting an appropriate technique for the research problem posed. Furthermore, how the approaches designed to test the robustness of the rankings within the same technique are implemented may differ, which may also lead to different results using the same research technique. It poses a significant problem in analyzing the sensitivity of rankings calculated from MCDA methods. Establishing standardized tools in this area will allow for the possibility of comparing results with each other, along with increased access to multiple sensitivity analysis techniques, which can also contribute to increasing the level of comprehensiveness of the ranking robustness assessments performed.

From the papers included in the review, it is apparent that considerable attention has been directed towards investigating the impact of changing the criteria weights on the resulting rankings. Various

approaches have been used for this purpose, such as the creation of different scenarios based on the prioritization of different criteria, the creation of new weight vectors based on systematic changes to the initial values of the criteria weights, or the use of probabilistic simulations to determine the probability of selection for different values of the weights. In contrast, as the descriptions of the selected frameworks have shown, it is only one way of testing the robustness of rankings to change. The popularity of this approach may be since generating a new vector of weights and using it in multi-criteria recalculations is a relatively easy task compared to designing an experiment to investigate changes in selected values in the decision matrix or benchmarking different MCDA methods using selected metrics. The results obtained by examining changes in the magnitude of criteria weights in decision problems is an important element of sensitivity analysis techniques in decision making, as many MCDA methods rely on this vector of weights in their calculations. However, this analysis should not rely solely on this approach. Instead, it should be used as a complement to, or as one element of the overall sensitivity analysis carried out to investigate the stability of the rankings. In this way, the conclusions, insights, and additional knowledge from such a study can contribute more to the decision-makers awareness of the decision problem at hand. It would enable the decision maker to make a more informed decision, as he/she would have information on potential rating scenarios depending on different initial factors.

As the results of the conducted review showed, the frequency of application of particular techniques for sensitivity analysis of results from multi-criteria models is not directly proportional to the amount and quality of information a particular technique provides. The selected techniques have a significantly higher contribution to the study of the robustness of the rankings to change than the others. However, they do not provide more benefits and valuable insights from potential changes in the decision model. The review research has shown that modifications to the values of the criteria weights are the most commonly used approach. The analysis of results when considering vectors of weights with different value distributions is simple to perform, but the conclusions it provides are superficial compared to the possibilities guaranteed by the other sensitivity analysis techniques in applied decision-making problems. In addition, the possibilities to make inferences based on the results from studies devoted only to changing the value of the weights are limited. Techniques focusing on this area of research should be used as part of an overall comprehensive ranking robustness research approach, where research directed at determining the impact of changes in the decision matrix, the probability of changes based on probabilistic simulations, or comparing available metrics and methods in decision-making guarantee additional knowledge in terms of the stability of the results. It challenges researchers who investigate multi-criteria problems to include a broader aspect of sensitivity analysis research in their work so that the results presented can become more valuable by considering the various parameters that potentially affect the differences that appear in the rankings and proposed choices.

Sensitivity analysis in decision-making is an important element because of the benefits of the additional knowledge that can be indicated by examining the robustness of the results to change. This process allows the identification of values that cause specific changes in rankings, allowing decision-makers to make more informed decisions based on the totality of the information provided. As can be seen, the use of sensitivity analysis is a popular approach to testing the robustness of decision models. However, many proposed systems still do not incorporate sensitivity testing of rankings or do not take a comprehensive approach to their research. It is vital to learn about potential outcome scenarios depending on the modeled change in the decision model, thus providing the decision-maker with the knowledge that presents him/her with different choices are given varying initial conditions. Proposed systems based on MCDA methods often focus on evaluating multiple decision variants with slightly different evaluations. It makes it worthwhile to investigate how robust the proposed solutions are, as marginal changes in the initial data values can affect the emergence of differences in the calculated rankings. It is directly related to the possibility of inaccurate data representation and measurement errors, which should be considered in decision-making problems. Equipping decision-making systems with additional mechanisms focusing on sensitivity analysis contributes to their reliability and enables the decision-maker with a more comprehensive knowledge of the given problem so that the chance of making valid and rational choices can be maximized.

6. Conclusions

Decision support models are constantly being developed due to their usefulness and high practical potential. To provide a comprehensive analysis of the decision space under examination, sensitivity analysis techniques are used. It also allows the relationship between the output and the input of the process to be explored, which contributes to gaining additional knowledge regarding potential changes to the proposed results. As these fields continuously develop and new methodologies and approaches are proposed to examine decision-making problems, it is important to take advantage of the latest available developments. However, the current state of the art and works in this area have not been updated, or have focused on applying decision models based on sensitivity analysis in selected practical areas. To fill the emerging gap and systematize knowledge in this area, a review research study was undertaken on how sensitivity analysis techniques are applied in Multi-Criteria Decision Analysis.

Based on the selected steps of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, the literature review of research papers directed to the sensitivity analysis and Multi-Criteria Decision Analysis was performed. The research focused on papers published after 2014 to provide an up-to-date overview of the used approaches. The review results were presented regarding the popularity of this field in the literature. The distribution of the papers included in the review was presented considering the year of publication, the practical area of application, and the sensitivity analysis technique applied in the study. The approaches used by the researchers were described to present how the sensitivity analysis is performed in different problems concerning the MCDA systems. Based on the conducted review, the main categories of sensitivity analysis approaches were identified and presented regarding their scope and purpose. Moreover, the practical implications of applying techniques from given categories were indicated. Then, the selected sensitivity analysis frameworks were presented and compared regarding the proposed research methodologies.

An analysis of the techniques used to examine the robustness of rankings to changes in multi-criteria decision-making has identified challenges and difficulties to be tackled in the context of sensitivity analysis. These relate to broadening the scope of sensitivity analyses currently conducted, which are often limited to examining changes in rankings in response to modifications to the criteria weights. It is worth conducting more comprehensive studies of ranking robustness, which focus on using a variety of approaches to study the impact of changes on performance, thus obtaining more meaningful information based on which informed and rational choices can be made.

The review conducted indicates the approaches currently used in the area of sensitivity analysis combined with Multi-Criteria Decision Analysis. The categories of sensitivity analysis techniques identified and presented make it possible to determine in which area of techniques a course of research directed at determining the robustness of rankings to change can be planned. An indication of the challenges encountered by current decision support systems using sensitivity analysis highlights what needs to be emphasized in future research to increase the level of reliability of the use of such systems.

CRediT authorship contribution statement

Jakub Więckowski: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Wojciech Sałabun:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] A. Ishizaka, P. Nemery, Multi-Criteria Decision Analysis: Methods and Software, John Wiley & Sons, 2013.
[2] J. Razmak, B. Aouni, Decision support system and multi-criteria decision aid: a state of the art and perspectives, J. Multi-Crit. Decis. Anal. 22 (1–2) (2015) 101–117.
[3] M. Aruldoss, T.M. Lakshmi, V.P. Venkatesan, A survey on multi criteria decision making methods and its applications, Am. J. Inf. Syst. 1 (1) (2013) 31–43.
[4] V. Brookes, M. Hernandez-Jover, B. Cowled, P. Holyoake, M. Ward, Building a picture: Prioritisation of exotic diseases for the pig industry in Australia using multi-criteria decision analysis, Prevent. Vet. Med. 113 (1) (2014) 103–117.
[5] S.K. Sahoo, S.S. Goswami, A Comprehensive Review of Multiple Criteria Decision-Making (MCDM) Methods: Advancements, Applications, and Future Directions, Decis. Mak. Adv. 1 (1) (2023) 25–48.
[6] W. Sałabun, J. Wątróbski, A. Shekhovtsov, Are MCDA Methods Benchmarkable? A Comparative Study of TOPSIS, VIKOR, COPRAS, and PROMETHEE II Methods, Symmetry 12 (9) (2020) 1549.
[7] J. Wątróbski, A. Bączkiewicz, W. Sałabun, pyrepo-mcda—Reference objects based MCDA software package, SoftwareX 19 (2022) 101107.
[8] I. Mukhametzyanov, On the conformity of scales of multidimensional normalization: An application for the problems of decision making, Decis. Mak.: Appl. Manage. Eng. 6 (1) (2023) 399–432.
[9] B. Paradowski, W. Sałabun, Are the results of MCDA methods reliable? Selection of materials for Thermal Energy Storage, Procedia Comput. Sci. 192 (2021) 1313–1322.
[10] G. Odu, Weighting methods for multi-criteria decision making technique, J. Appl. Sci. Environ. Manage. 23 (8) (2019) 1449–1457.
[11] Ž. Stević, E.K. Zavadskas, F.M. Tawfiq, F. Tchier, T. Davidov, Fuzzy Multicriteria Decision-Making Model Based on Z Numbers for the Evaluation of Information Technology for Order Picking in Warehouses, Appl. Sci. 12 (24) (2022) 12533.
[12] Ž. Stević, A. Ulutaş, S. Korucuk, S. Memiş, E. Demir, A. Topal, Ç. Karamaşa, et al., Supply Chain Management (SCM) Breakdowns and SCM Strategy Selection during the COVID-19 Pandemic Using the Novel Rough MCDM Model, Complexity 2023 (2023).
[13] B. Kizielewicz, J. Więckowski, J. Wątrobski, A study of different distance metrics in the TOPSIS method, in: Intelligent Decision Technologies: Proceedings of the 13th KES-IDT 2021 Conference, Springer, 2021, pp. 275–284.
[14] A. Ali, K. Ullah, A. Hussain, An approach to multi-attribute decision-making based on intuitionistic fuzzy soft information and Aczel-Alsina operational laws, J. Decis. Anal. Intell. Comput. 3 (1) (2023) 80–89.
[15] M.R. Khan, K. Ullah, Q. Khan, Multi-attribute decision-making using Archimedean aggregation operator in T-spherical fuzzy environment, Rep. Mech. Eng. 4 (1) (2023) 18–38.
[16] B. Yatsalo, A. Korobov, A. Radaev, J. Qin, L. Martínez, Ranking of independent and dependent fuzzy numbers and intransitivity in fuzzy MCDA, IEEE Trans. Fuzzy Syst. 30 (5) (2021) 1382–1395.
[17] A. Saltelli, S. Tarantola, K. Chan, A role for sensitivity analysis in presenting the results from MCDA studies to decision makers, J. Multi-Crit. Decis. Anal. 8 (3) (1999) 139–145.
[18] J. Zheng, C. Egger, J. Lienert, A scenario-based MCDA framework for wastewater infrastructure planning under uncertainty, J. Environ. Manage. 183 (2016) 895–908.
[19] B. Iooss, A. Saltelli, Introduction to sensitivity analysis, in: Handbook of Uncertainty Quantification, Springer, 2017, pp. 1103–1122.
[20] D. Bozanic, D. Tešić, D. Marinković, A. Milić, Modeling of neuro-fuzzy system as a support in decision-making processes, Rep. Mech. Eng. 2 (1) (2021) 222–234.
[21] K. Hyde, H.R. Maier, C. Colby, Incorporating uncertainty in the PROMETHEE MCDA method, J. Multi-Crit. Decis. Anal. 12 (4–5) (2003) 245–259.
[22] D. Pamucar, S. Biswas, A Novel Hybrid Decision Making Framework for Comparing Market Performance of Metaverse Crypto Assets, Decis. Mak. Adv. 1 (1) (2023) 49–62.
[23] E. Mahmutagić, Ž. Stević, Z. Nunić, P. Chatterjee, I. Tanackov, An integrated decision-making model for efficiency analysis of the forklifts in warehousing systems, Facta Univ. Ser.: Mech. Eng. 19 (3) (2021) 537–553.
[24] Z. Pang, Z. O'Neill, Y. Li, F. Niu, The role of sensitivity analysis in the building performance analysis: A critical review, Energy Build. 209 (2020) 109659.
[25] F. Pianosi, K. Beven, J. Freer, J.W. Hall, J. Rougier, D.B. Stephenson, T. Wagener, Sensitivity analysis of environmental models: A systematic review with practical workflow, Environ. Model. Softw. 79 (2016) 214–232.
[26] A. Saltelli, M. Ratto, S. Tarantola, F. Campolongo, Sensitivity analysis for chemical models, Chem. Rev. 105 (7) (2005) 2811–2828.
[27] G. Baio, A.P. Dawid, Probabilistic sensitivity analysis in health economics, Stat. Methods Med. Res. 24 (6) (2015) 615–634.
[28] C.N. Rao, M. Sujatha, A consensus-based Fermatean fuzzy WASPAS methodology for selection of healthcare waste treatment technology selection, Decis. Mak.: Appl. Manage. Eng. 6 (2) (2023) 600–619.
[29] I. Badi, Ž. Stević, M.B. Bouraima, Overcoming obstacles to renewable energy development in libya: an MCDM Approach towards effective strategy formulation, Decis. Mak. Adv. 1 (1) (2023) 17–24.
[30] R. Krishankumar, D. Pamucar, Solving barrier ranking in clean energy adoption: An MCDM approach with q-rung orthopair fuzzy preferences, Int. J. Knowl.-Based Intell. Eng. Syst. (Preprint) (2023) 1–18.
[31] P. Chatterjee, V.M. Athawale, S. Chakraborty, Materials selection using complex proportional assessment and evaluation of mixed data methods, Mater. Des. 32 (2) (2011) 851–860.
[32] S. Chatterjee, S. Chakraborty, A Multi-criteria decision making approach for 3D printer nozzle material selection, Rep. Mech. Eng. 4 (1) (2023) 62–79.
[33] M. Damjanović, Ž. Stević, D. Stanimirović, I. Tanackov, D. Marinković, Impact of the number of vehicles on traffic safety: multiphase modeling, Facta Univ. Ser.: Mech. Eng. 20 (1) (2022) 177–197.
[34] I. Đalić, Ž. Stević, J. Ateljević, Z. Turskis, E.K. Zavadskas, A. Mardani, A novel integrated MCDM-SWOT-TOWS model for the strategic decision analysis in transportation company, Facta Univ. Ser.: Mech. Eng. 19 (3) (2021) 401–422.
[35] D. Tešić, D. Božanić, A. Puška, A. Milić, D. Marinković, Development of the MCDM fuzzy LMAW-grey MARCOS model for selection of a dump truck, Rep. Mech. Eng. 4 (1) (2023) 1–17.
[36] P. Chatterjee, M. Yazdani, S. Chakraborty, Sustainability Modeling in Engineering: A Multi-Criteria Perspective, World Scientific, 2019.
[37] Q. Liu, TOPSIS Model for evaluating the corporate environmental performance under intuitionistic fuzzy environment, Int. J. Knowl.-Based Intell. Eng. Syst. 26 (2) (2022) 149–157.
[38] A. Rappaport, Sensitivity analysis in decision making, Account. Rev. 42 (3) (1967) 441–456.
[39] M.G. Delgado, J.B. Sendra, Sensitivity analysis in multicriteria spatial decision-making: a review, Hum. Ecol. Risk Assess. 10 (6) (2004) 1173–1187.
[40] L. Andronis, P. Barton, S. Bryan, Sensitivity analysis in economic evaluation: an audit of NICE current practice and a review of its use and value in decision-making., Health Technol. Assess. (Winch. Engl.) 13 (29) (2009) iii–ix.
[41] M. Ginocchi, F. Ponci, A. Monti, Sensitivity Analysis and Power Systems: Can We Bridge the Gap? A Review and a Guide to Getting Started, Energies 14 (24) (2021) 8274.
[42] R. Sarkis-Onofre, F. Catalá-López, E. Aromataris, C. Lockwood, How to properly use the PRISMA Statement, Syst. Rev. 10 (1) (2021) 1–3.
[43] J. Więckowski, GitHub repository with research papers included in the systematic review, 2023, [Online; accessed XX-XXXX-2023], https://github.com/jwieckowski/research/tree/main/Sensitivity%20Analysis%20review.
[44] F.A. Ferreira, R.W. Spahr, M.A. Sunderman, Using multiple criteria decision analysis (MCDA) to assist in estimating residential housing values, Int. J. Strateg. Prop. Manag. 20 (4) (2016) 354–370.
[45] A.H. Salimi, A. Noori, H. Bonakdari, J. Masoompour Samakosh, E. Sharifi, M. Hassanvand, B. Gharabaghi, M. Agharazi, Exploring the role of advertising types on improving the water consumption behavior: An application of integrated fuzzy AHP and fuzzy VIKOR method, Sustainability 12 (3) (2020) 1232.
[46] B. Muñoz, M.G. Romana, J. Ordóñez, Sensitivity Analysis of Multicriteria Decision Making Methodology Developed for Selection of Typologies of Earth-retaining Walls in an Urban Highway, Transp. Res. Proc. 18 (2016) 135–139.
[47] J.S. Jeong, D. González-Gómez, Adapting to PSTs' pedagogical changes in sustainable mathematics education through flipped E-Learning: Ranking its criteria with MCDA/F-DEMATEL, Mathematics 8 (5) (2020) 858.

[48] T. Østergård, R.L. Jensen, S.E. Maagaard, Early Building Design: Informed decision-making by exploring multidimensional design space using sensitivity analysis, Energy Build. 142 (2017) 8–22.
[49] O. Ghorbanzadeh, B. Feizizadeh, T. Blaschke, Multi-criteria risk evaluation by integrating an analytical network process approach into GIS-based sensitivity and uncertainty analyses, Geomat. Nat. Hazards Risk 9 (1) (2018) 127–151.
[50] A. Ganji, H.R. Maier, G.C. Dandy, A modified Sobol sensitivity analysis method for decision-making in environmental problems, Environ. Model. Softw. 75 (2016) 15–27.
[51] Z.-p. Tian, J.-q. Wang, H.-y. Zhang, An integrated approach for failure mode and effects analysis based on fuzzy best-worst, relative entropy, and VIKOR methods, Appl. Soft Comput. 72 (2018) 636–646.
[52] J. Qin, X. Liu, W. Pedrycz, An extended TODIM multi-criteria group decision making method for green supplier selection in interval type-2 fuzzy environment, European J. Oper. Res. 258 (2) (2017) 626–638.
[53] Y. Wu, F. He, J. Zhou, C. Wu, F. Liu, Y. Tao, C. Xu, Optimal site selection for distributed wind power coupled hydrogen storage project using a geographical information system based multi-criteria decision-making approach: A case in China, J. Clean. Prod. 299 (2021) 126905.
[54] S. Stoycheva, D. Marchese, C. Paul, S. Padoan, A.-s. Juhmani, I. Linkov, Multi-criteria decision analysis framework for sustainable manufacturing in automotive industry, J. Clean. Prod. 187 (2018) 257–272.
[55] S.H. Zyoud, L.G. Kaufmann, H. Shaheen, S. Samhan, D. Fuchs-Hanusch, A framework for water loss management in developing countries under fuzzy environment: Integration of Fuzzy AHP with Fuzzy TOPSIS, Expert Syst. Appl. 61 (2016) 86–105.
[56] O. Taylan, R. Alamoudi, M. Kabli, A. AlJifri, F. Ramzi, E. Herrera-Viedma, Assessment of energy systems using extended fuzzy AHP, fuzzy VIKOR, and TOPSIS approaches to manage non-cooperative opinions, Sustainability 12 (7) (2020) 2745.
[57] B.B.T.d. Carmo, M. Margni, P. Baptiste, Ranking product systems based on uncertain life cycle sustainability assessment: A stochastic multiple criteria decision analysis approach, Revista Admin. UFSM 13 (2021) 850–874.
[58] Z. Asif, Z. Chen, An Integrated Multicriteria Decision Analysis System for Reducing Air Emissions from Mining Process, Environ. Model. Assess. 24 (2019) 517–531.
[59] S.A. Dabous, W. Zeiada, T. Zayed, R. Al-Ruzouq, Sustainability-informed multi-criteria decision support framework for ranking and prioritization of pavement sections, J. Clean. Prod. 244 (2020) 118755.
[60] Y. Lin, J. Hoover, D. Beene, E. Erdei, Z. Liu, Environmental risk mapping of potential abandoned uranium mine contamination on the Navajo Nation, USA, using a GIS-based multi-criteria decision analysis approach, Environ. Sci. Pollut. Res. 27 (2020) 30542–30557.
[61] C.R. Matos, J.F. Carneiro, P. Pereira da Silva, C.O. Henriques, A GIS-MCDA Approach Addressing Economic-Social-Environmental Concerns for Selecting the Most Suitable Compressed Air Energy Storage Reservoirs, Energies 14 (20) (2021) 6793.
[62] M.M. de Brito, A. Almoradie, M. Evers, Spatially-explicit sensitivity and uncertainty analysis in a MCDA-based flood vulnerability model, Int. J. Geogr. Inf. Sci. 33 (9) (2019) 1788–1806.
[63] E. Ayyildiz, M. Erdogan, A. Taskin Gumus, A Pythagorean fuzzy number-based integration of AHP and WASPAS methods for refugee camp location selection problem: a real case study for Istanbul, Turkey, Neural Comput. Appl. 33 (22) (2021) 15751–15768.
[64] S. Ding, J. Xu, L. Dai, H. Hu, Mobility industry call center location selection under sustainability: a two-phase decision-making approach, Smart Resil. Transp. 3 (2) (2021) 177–201.
[65] J. Gao, F. Guo, Z. Ma, X. Huang, Multi-criteria decision-making framework for large-scale rooftop photovoltaic project site selection based on intuitionistic fuzzy sets, Appl. Soft Comput. 102 (2021) 107098.
[66] C.-N. Wang, T.-T. Dang, et al., Location optimization of wind plants using DEA and fuzzy multi-criteria decision making: A case study in Vietnam, IEEE Access 9 (2021) 116265–116285.
[67] Y. Wu, Y. Tao, B. Zhang, S. Wang, C. Xu, J. Zhou, A decision framework of offshore wind power station site selection using a PROMETHEE method under intuitionistic fuzzy environment: A case in China, Ocean Coast. Manage. 184 (2020) 105016.
[68] D.S. Pamučar, D. Božanić, A. Ranđelović, Multi-criteria decision making: An example of sensitivity analysis, Serb. J. Manage. 12 (1) (2017) 1–27.
[69] V. Diaby, K. Campbell, R. Goeree, Multi-criteria decision analysis (MCDA) in health care: a bibliometric analysis, Oper. Res. Health C. 2 (1–2) (2013) 20–24.
[70] A.C. Mühlbacher, A. Kaczynski, Making good decisions in healthcare with multi-criteria decision analysis: the use, current research and future development of MCDA, Appl. Health Econ. Health Policy 14 (2016) 29–40.
[71] Z. Wang, F. Xiao, W. Ding, Interval-valued intuitionistic fuzzy Jenson-Shannon divergence and its application in multi-attribute decision making, Appl. Intell. (2022) 1–17.
[72] N. Ghorui, A. Ghosh, S.P. Mondal, M.Y. Bajuri, A. Ahmadian, S. Salahshour, M. Ferrara, Identification of dominant risk factor involved in spread of COVID-19 using hesitant fuzzy MCDM methodology, Res. Phys. 21 (2021) 103811.
[73] F. Ecer, D. Pamucar, MARCOS technique under intuitionistic fuzzy environment for determining the COVID-19 pandemic performance of insurance companies in terms of healthcare services, Appl. Soft Comput. 104 (2021) 107199.
[74] W. Looman, N. Bleijenberg, M. Karimi, M. Hoedemakers, N. de Wit, M.R.-v. Mölken, Multi-criteria decision analysis of a proactive person-centred integrated primary care program care for frail elderly in the Netherlands: U-PROFIT., Int. J. Integr. Care (IJIC) 19 (2019).
[75] C.N. Peters, H. Baroud, G.M. Hornberger, et al., Multicriteria decision analysis of drinking water source selection in southwestern Bangladesh, J. Water Resour. Plan. Manag. 145 (2019) 05019004.
[76] S. Schug, E. Pogatzki-Zahn, L.D. Phillips, M.N. Essex, F. Xia, A.J. Reader, R. Pawinski, Multi-criteria decision analysis to develop an efficacy-safety profile of parenteral analgesics used in the treatment of postoperative pain, J. Pain Res. (2020) 1969–1977.
[77] B. Reddy, M. Kelly, P. Thokala, S. Walters, A. Duenas, Prioritising public health guidance topics in the National Institute for Health and Care Excellence using the Analytic Hierarchy Process, Public Health 128 (10) (2014) 896–903.
[78] C.R. Chapple, E. Mironska, A. Wagg, I. Milsom, D.C. Diaz, H. Koelbl, D. Pushkar, A. Tubaro, D. De Ridder, E. Chartier-Kastler, et al., Multicriteria decision analysis applied to the clinical use of pharmacotherapy for overactive bladder symptom complex, Eur. Urol. Focus 6 (3) (2020) 522–530.
[79] V. Diaby, R. Goeree, How to use multi-criteria decision analysis methods for reimbursement decision-making in healthcare: a step-by-step guide, Expert Rev. Pharmacoecon. Outcomes Res. 14 (1) (2014) 81–99.
[80] M.-A. Etim, S. Academe, P. Emenike, D. Omole, Application of multi-criteria decision approach in the assessment of medical waste management systems in Nigeria, Sustainability 13 (19) (2021) 10914.
[81] M. Deveci, Site selection for hydrogen underground storage using interval type-2 hesitant fuzzy sets, Int. J. Hydrogen Energy 43 (19) (2018) 9353–9368.
[82] M. Yazdani, D. Pamucar, P. Chatterjee, S. Chakraborty, Development of a decision support framework for sustainable freight transport system evaluation using rough numbers, Int. J. Prod. Res. 58 (14) (2020) 4325–4351.
[83] J.-P. Chang, Z.-S. Chen, S.-H. Xiong, J. Zhang, K.-S. Chin, Intuitionistic fuzzy multiple criteria group decision making: A consolidated model with application to emergency plan selection, IEEE Access 7 (2019) 41958–41980.
[84] D. Xu, L. Dong, Comprehensive evaluation of sustainable ammonia production systems based on fuzzy multiattribute decision making under hybrid information, Energy Sci. Eng. 8 (6) (2020) 1902–1923.
[85] D. Panchal, P. Chatterjee, R. Sharma, R.K. Garg, Sustainable oil selection for cleaner production in Indian foundry industries: A three phase integrated decision-making framework, J. Clean. Prod. 313 (2021) 127827.
[86] O. Dogan, Process mining technology selection with spherical fuzzy AHP and sensitivity analysis, Expert Syst. Appl. 178 (2021) 114999.
[87] A. Hashemizadeh, Y. Ju, S.M.H. Bamakan, H.P. Le, Renewable energy investment risk assessment in belt and road initiative countries under uncertainty conditions, Energy 214 (2021) 118923.
[88] V. Maliene, R. Dixon-Gough, N. Malys, Dispersion of relative importance values contributes to the ranking uncertainty: Sensitivity analysis of Multiple Criteria Decision-Making methods, Appl. Soft Comput. 67 (2018) 286–298.
[89] E.P. Kechagias, S.P. Gayialis, G.D. Konstantakopoulos, G.A. Papadopoulos, An application of a multi-criteria approach for the development of a process reference model for supply chain operations, Sustainability 12 (14) (2020) 5791.
[90] I. Fuentes, R.W. Vervoort, Site suitability and water availability for a managed aquifer recharge project in the Namoi basin, Australia, J. Hydrol.: Reg. Stud. 27 (2020) 100657.
[91] E. Pagone, K. Salonitis, M. Jolly, Automatically weighted high-resolution mapping of multi-criteria decision analysis for sustainable manufacturing systems, J. Clean. Prod. 257 (2020) 120272.
[92] F. Russo, C. Oreto, R. Veropalumbo, A practice for the application of waste in road asphalt pavements in an eco-friendly way, Appl. Sci. 11 (19) (2021) 9268.
[93] O. Agboola, B. Akinnuli, B. Kareem, M. Akintunde, Decision on the selection of the best height-diameter ratio for the optimal design of 13,000 m3 oil storage tank, Cogent Eng. 7 (1) (2020) 1770913.
[94] A. Feizi, S. Joo, V. Kwigizile, J.-S. Oh, A pervasive framework toward sustainability and smart-growth: Assessing multifaceted transportation performance measures for smart cities, J. Transp. Health 19 (2020) 100956.
[95] J.M. Humphries Choptiany, R. Pelot, A multicriteria decision analysis model and risk assessment framework for carbon capture and storage, Risk Anal. 34 (9) (2014) 1720–1737.
[96] J.-C. Maréchal, M. Bouzit, J.-D. Rinaudo, F. Moiroux, J.-F. Desprats, Y. Caballero, Mapping economic feasibility of managed aquifer recharge, Water 12 (3) (2020) 680.
[97] R.M. Elavarasan, S. Leoponraj, J. Vishnupriyan, A. Dheeraj, G.G. Sundar, Multi-Criteria Decision Analysis for user satisfaction-induced demand-side load management for an institutional building, Renew. Energy 170 (2021) 1396–1426.
[98] T.D.S. Manikkuwahandi, G.M. Hornberger, H. Baroud, Decision analysis for expansion of Mahaweli multipurpose reservoir system in Sri Lanka, J. Water Resour. Plann. Manage. 145 (9) (2019) 05019013.

[99] A. Alinezhad, K. Sarrafha, A. Amini, Sensitivity analysis of SAW technique: The impact of changing the decision making matrix elements on the final ranking of alternatives, Iran. J. Oper. Res. 5 (1) (2014) 82–94.
[100] Ž. Stević, D. Pamučar, A. Puška, P. Chatterjee, Sustainable supplier selection in healthcare industries using a new MCDM method: Measurement of alternatives and ranking according to COmpromise solution (MARCOS), Comput. Ind. Eng. 140 (2020) 106231.
[101] Ü. Şengül, M. Eren, S.E. Shiraz, V. Gezder, A.B. Şengül, Fuzzy TOPSIS method for ranking renewable energy supply systems in Turkey, Renew. Energy 75 (2015) 617–625.
[102] B. Feizizadeh, P. Jankowski, T. Blaschke, A GIS based spatially-explicit sensitivity and uncertainty analysis approach for multi-criteria decision analysis, Comput. Geosci. 64 (2014) 81–95.
[103] E.B. Tirkolaee, A. Mardani, Z. Dashtian, M. Soltani, G.-W. Weber, A novel hybrid method using fuzzy decision making and multi-objective programming for sustainable-reliable supplier selection in two-echelon supply chain design, J. Clean. Prod. 250 (2020) 119517.
[104] F. Ecer, D. Pamucar, Sustainable supplier selection: A novel integrated fuzzy best worst method (F-BWM) and fuzzy CoCoSo with Bonferroni (CoCoSo'B) multi-criteria model, J. Clean. Prod. 266 (2020) 121981.
[105] M. Çolak, İ. Kaya, Prioritization of renewable energy alternatives by using an integrated fuzzy MCDM model: A real case application for Turkey, Renew. Sustain. Energy Rev. 80 (2017) 840–853.
[106] M. Keshavarz-Ghorabaee, M. Amiri, E.K. Zavadskas, Z. Turskis, J. Antucheviciene, Determination of objective weights using a new method based on the removal effects of criteria (MEREC), Symmetry 13 (4) (2021) 525.
[107] L. Wang, H.-y. Zhang, J.-q. Wang, L. Li, Picture fuzzy normalized projection-based VIKOR method for the risk evaluation of construction project, Appl. Soft Comput. 64 (2018) 216–226.
[108] G. Kou, Ö. Olgu Akdeniz, H. Dinçer, S. Yüksel, Fintech investments in European banks: a hybrid IT2 fuzzy multidimensional decision-making approach, Financ. Innov. 7 (1) (2021) 39.
[109] D. Souissi, L. Zouhri, S. Hammami, M.H. Msaddek, A. Zghibi, M. Dlala, GIS-based MCDM–AHP modeling for flood susceptibility mapping of arid areas, southeastern Tunisia, Geocarto Int. 35 (9) (2020) 991–1017.
[110] R. Alizadeh, L. Soltanisehat, P.D. Lund, H. Zamanisabzi, Improving renewable energy policy planning and decision-making through a hybrid MCDM method, Energy Policy 137 (2020) 111174.
[111] M. Abdel-Basset, A. Gamal, R.K. Chakrabortty, M. Ryan, A new hybrid multi-criteria decision-making approach for location selection of sustainable offshore wind energy stations: A case study, J. Clean. Prod. 280 (2021) 124462.
[112] X. Peng, X. Zhang, Z. Luo, Pythagorean fuzzy MCDM method based on CoCoSo and CRITIC with score function for 5G industry evaluation, Artif. Intell. Rev. 53 (5) (2020) 3813–3847.
[113] Ž. Stević, N. Brković, A novel integrated FUCOM-MARCOS model for evaluation of human resources in a transport company, Logistics 4 (1) (2020) 4.
[114] I. Mukhametzyanov, D. Pamucar, A sensitivity analysis in MCDM problems: A statistical approach, Decis. Mak.: Appl. Manage. Eng. 1 (2) (2018) 51–80.
[115] A. Çalık, A novel Pythagorean fuzzy AHP and fuzzy TOPSIS methodology for green supplier selection in the Industry 4.0 era, Soft Comput. 25 (3) (2021) 2253–2265.
[116] L. Gigović, D. Pamučar, D. Lukić, S. Marković, GIS-Fuzzy DEMATEL MCDA model for the evaluation of the sites for ecotourism development: A case study of "Dunavski ključ" region, Serbia, Land Use Policy 58 (2016) 348–365.
[117] A. Ligmann-Zielinska, P. Jankowski, A framework for sensitivity analysis in spatial multiple criteria evaluation, in: Geographic Information Science: 5th International Conference, GIScience 2008, Park City, UT, USA, September 23-26, 2008. Proceedings 5, Springer, 2008, pp. 217–233.
[118] A. Moreno-Calderón, T.S. Tong, P. Thokala, Multi-criteria decision analysis software in healthcare priority setting: a systematic review, Pharmacoeconomics 38 (2020) 269–283.
[119] E. Triantaphyllou, A. Sánchez, A sensitivity analysis approach for some deterministic multi-criteria decision-making methods, Decis. Sci. 28 (1) (1997) 151–194.
[120] L. Proll, A. Salhi, D. Rios Insua, Improving an optimization-based framework for sensitivity analysis in multi-criteria decision-making, J. Multi-Crit. Decis. Anal. 10 (1) (2001) 1–9.
[121] S.R. Nabavi, Z. Wang, G.P. Rangaiah, Sensitivity Analysis of Multi-Criteria Decision-Making Methods for Engineering Applications, Ind. Eng. Chem. Res. (2023).
[122] M.J.M. Haddad, A framework that uses sensitivity analysis to select multi criteria decision making methods, J. Comput. Syst. Eng. (2017) 413–419.
[123] W. Wolters, B. Mareschal, Novel types of sensitivity analysis for additive MCDM methods, European J. Oper. Res. 81 (2) (1995) 281–290.