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REVIEW ARTICLE

Fuzzy Multicriteria Decision-Making: A Literature Review*

Cengiz Kahraman†
Department of Industrial Engineering, Istanbul Technical University, Macka Istanbul, Turkey

Sezi Cevik Onar
Department of Industrial Engineering, Istanbul Technical University, Macka Istanbul, Turkey

Basar Oztaysi
Department of Industrial Engineering, Istanbul Technical University, Macka Istanbul, Turkey

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Abstract

Multicriteria decision-making (MCDM) refers to making decisions in the presence of multiple and usually conflicting criteria. Fuzzy decision-making is used where vague and incomplete data exist for the solution. Fuzzy multicriteria decision-making is one of the most popular problems handled by the researchers in the literature. In this paper, we survey the latest status of fuzzy multicriteria decision-making methods and classify these methods dividing into two parts: fuzzy multiattribute decision-making (MADM) and fuzzy multiobjective decision-making (MODM). Most of the publications are on fuzzy MADM since there are a plenty of classical multiattribute decision-making methods in the literature. Tabular and graphical illustrations for each method are given.

Keywords: Multicriteria, multiobjective, multiattribute, fuzzy decision making, classification

†kahramanc@itu.edu.tr

1. Introduction

Real-world decision-making problems are usually too complex and ill-structured to be considered through the examination of a single criterion that will lead to the optimum decision. In fact, such a unidimensional approach is merely an oversimplification of the actual nature of the problem at hand, and it can lead to unrealistic decisions. A more appealing approach would be the simultaneous consideration of all pertinent factors that are related to the problem. Multicriteria Decision Making (MCDM) constitutes an advanced field of operations research that is devoted to the development and implementation of decision support tools and methodologies to confront complex decision problems involving multiple criteria, goals, or objectives of conflicting nature [1].

Problems where the decision maker must evaluate a finite set of alternatives in order to select the most appropriate one and to rank them from the best to the worst are called discrete MCDM problems while problems where there is an infinite set of alternatives are called continuous MCDM problems. Discrete MCDM problems are addressed through the multiattribute decision making (MADM) methods while continuous MCDM problems are addressed through multiobjective decision making (MODM) methods.

Fuzzy MCDM models are used to assess alternatives with respect to predetermined criteria through either a single decision maker or a committee of decision makers, where suitability of alternatives versus criteria, and the importance weights of criteria can be evaluated using linguistic values represented by fuzzy numbers [2]. A linguistic variable is a variable whose values are words or sentences in a natural or artificial language [3].

Numerous approaches have been proposed to solve fuzzy MCDM problems. A review and comparison of many of these methods can be found in [2],[4],[5] and [6]. Abdullah [7] presents a brief review of category in fuzzy multi criteria decision making and describes some of its earliest and recent applications. Several real life applications are presented to offer a glimpse of category in fuzzy multi criteria decision making and its applications.

The fuzzy set theory has been recently extended by developing new types of fuzzy sets. These include t*ype-2 fuzzy sets* and *type-n fuzzy sets* that incorporate uncertainty about the membership function in their definition [3]; *nonstationary fuzzy sets* that introduce into the membership functions a connection that expresses a slight variation in the membership function [8]; *Intuitionistic fuzzy sets,* introduced by Atanassov [9], extend fuzzy sets by an additional degree, which is called the degree of uncertainty; *fuzzy multisets* based on multisets that allow repeated elements in the set [10]; *hesitant fuzzy sets (HFS)* that have been recently introduced in [11] and provide a very interesting extension of fuzzy sets. HFS are especially useful when a set of values are possible to define the membership function of an element [12]. Recently *hesitant fuzzy linguistic term sets (HFTLS)* have been proposed to increase the richness of linguistic elicitation [13].

The aim of this paper is to summarize the present position of fuzzy MCDM research area. This summary includes the classification of fuzzy MCDM methods, the distributions of publications with respect to their subject areas, publication years, citation frequencies, authors, and publishing journals. We also classify the studies into three groups: The first group develops new fuzzy methodologies or modifies the existing approaches; second group uses the existing approaches in a specific problem area. Third group integrates different MCDM techniques. It also presents expected future trends on fuzzy MCDM. We reviewed the publications which were published after 1980 since it is almost the start of the fuzzy set theory's usage to extend the classical MCDM methods. Tabular and graphical works summarize the progress in fuzzy MCDM methodologies. The most used fuzzy MCDM methods are surveyed by analyzing the publishing frequencies with respect to years; the journals publishing fuzzy MCDM methods; the most cited papers on fuzzy MCDM methods, etc.

The rest of the paper is organized as follows. Section 2 presents the fuzzy MADM methods. Each of them is reviewed by some tabular and graphical illustrations. In Section 3, the similar tabular and graphical analyses are made for MODM methods used under fuzziness. Section 4 gives the expected future trends in fuzzy MCDM methods and Section 5 concludes the paper.

2. Fuzzy Multiattribute Decision Making

There are about 20 MADM methods in the literature [2] while MODM methods can only be categorized into three main groups [14]. In the following, we first classify and summarize the MADM methods used under fuzziness.

2.1. *Outranking methods*

2.1.1. ELECTRE

The acronym ELECTRE stands for ELimination Et Choix Traduisant la REalit´e (ELimination and Choice Expressing the REality) [15]. Preferences in ELECTRE methods are modeled by using a binary outranking relation whose meaning is "at least as good as". ELECTRE methods build one or several (crispy, fuzzy or embedded) outranking relations. Using outranking relations to model preferences introduces a new preference relation, R (incomparability). This relation is useful to account for situations in which the decision maker (DM) and/or the analyst are not able to compare two actions [16].

Roy [17] developed ELECTRE III method which uses fuzzy binary outranking relations. In ELECTRE III the outranking relation can be interpreted as a fuzzy relation. The construction of this relation requires the definition of a credibility index, which characterizes the credibility of the assertion "a outranks b". ELECTRE III was designed to improve ELECTRE II and thus deal with inaccurate, imprecise, uncertain or ill determination of data. This purpose was actually achieved, and ELECTRE III was applied with success on a broad range of real-life applications.

A literature review for fuzzy ELECTRE using SCOPUS gives 1,153 published papers (all fields). Among these, 70 papers mention fuzzy ELECTRE in "article title, abstract, or keywords" and 36 papers in their titles.

Leyva-López and Fernández-González [18] present an extension of the ELECTRE III multicriteria outranking methodology to assist a group of decision makers with different value systems to achieve a consensus on a set of possible alternatives. Their proposal starts with N individual rankings and N corresponding valued preference functions, and uses the natural heuristic provided by ELECTRE methodology for obtaining a fuzzy binary relation representing the collective preference. Belacel [19] presents a new fuzzy multicriteria classification method, called PRO AFTN, for assigning alternatives to predefined categories. This method belongs to the class of supervised learning algorithms and enables to determine the fuzzy indifference relations by generalizing the indices (concordance and discordance) used in the ELECTRE III method. Then, it assigns the fuzzy belonging degree of the alternatives to the categories. Figure 1 shows the number of published papers using fuzzy ELECTRE over years.

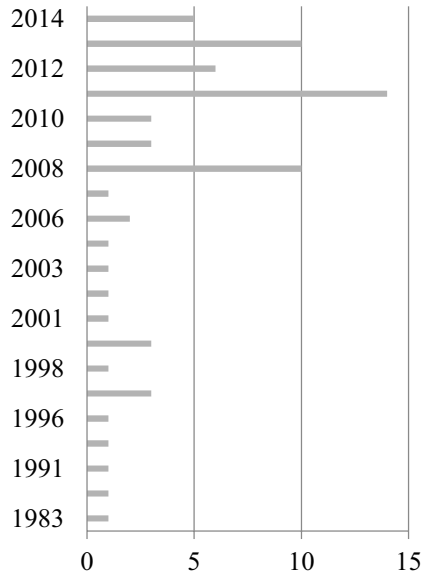

Figure 1. Published papers using fuzzy ELECTRE over years.

Table 1 shows the journals most-publishing fuzzy ELECTRE based articles.

Table 1. Journals that publish fuzzy ELECTRE based articles

Journal	Total
Expert Systems with Applications	4
Fuzzy Sets and Systems	4
European Journal of Operational Research	4
International Journal of Advanced Manufacturing Technology	3
Cybernetics and Systems	2

Figure 2 presents the subject areas of the examined papers using fuzzy ELECTRE.

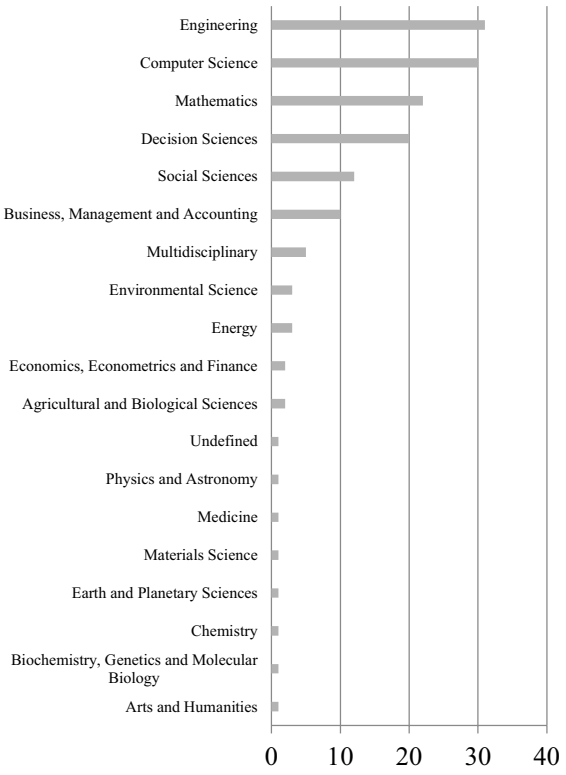

Figure 2. Subject areas of the examined papers using fuzzy ELECTRE.

Table 2 shows the most influential articles on fuzzy ELECTRE including their authors and cited times.

Table 2. Most influential articles on fuzzy ELECTRE

References	Publication Year	Cited times
Bender and Simonovic [20]	2000	95
Leyva-López and Fernández-González [18]	2003	85
Beccali et al., [21]	1998	59
Kangas et al., [22]	2001	55
Siskos and Hubert [23]	1983	46
Hatami-Marbini and Tavana [24]	2011	41
Montazer et al. [25]	2009	25

The authors C. Kahraman (with 3 publications) from Istanbul Technical University, E. Fernandez (with 3 publications) from Universidad Autonoma de Sinaloa, C. Rigopoulos (with 3 publications), M. Tavana (with 3 publications) from La Salle University, B. Vahdani from Islami Azad University (with 3 publications), and A. Hatami-Marbini (with 2 publications) from Universite Catholique de Louvain are the most productive researchers on fuzzy ELECTRE.

The fuzzy ELECTRE based studies can be grouped into 3 groups. The first group develops fuzzy ELECTRE methodologies or modifies the existing approaches: Hatami-Marbini and Tavana [24] address the gap in the ELECTRE literature for problems involving conflicting systems of criteria, uncertainty and imprecise information and extend the ELECTRE I method to take into account the uncertain, imprecise and linguistic assessments. They define outranking relations by pairwise comparisons and use decision graphs to determine which action is preferable, incomparable or indifferent in the fuzzy environment and show that contrary to the TOPSIS rankings, the ELECTRE approach reveals more useful information including the incomparability among the actions. Montazar et al. [25] discuss the architecture of a fuzzy system including both modules, utilizing fuzzy concept for dealing with the uncertainty of the problem. Their system comprises a fuzzy evaluation module, which is a fuzzy expert system and, an appropriate tool for evaluating the existing alternatives promptly and smoothly, without the imposed time delays, and a fuzzy ranking module, which is a fuzzy version of ELECTRE III method. Sevkli [26] compares crisp and fuzzy ELECTRE methods for supplier selection problem. He proposes a new fuzzy ELECTRE method and applies it to a manufacturing company in Turkey. After determining the criteria that affect the supplier selection decisions, the results for both crisp and fuzzy ELECTRE methods are presented. Vahdani and Hadipour [27] present the interval-valued fuzzy ELECTRE method aiming at solving MCDM problems in which the weights of criteria are unequal. For the purpose of proving the validity of the proposed model, they present a practical maintenance strategy selection problem. Bisdorff [28] introduces split truth/falseness semantics for a multi-valued logical processing of fuzzy preference modeling. The approach takes as starting point the standard framework of fuzzy outranking relations. Formal links between a given relational credibility calculus and associated truth polarization techniques are discussed. The main result is the establishment of a multi-valued logical framework which allows to naturally postpone any necessary defuzzification step to the end of the decision problem.

Second group uses the existent approaches in a specific problem area. Tolga [29] considers the software development project selection process in multicriteria thinking. The fuzzy ELECTRE method takes both fuzzy real option value criteria and nonmonetary criteria into account. Integration of fuzzy real options valuation to

fuzzy ELECTRE is presented for a selection process among software development projects. Rouyendegh and Erkan [30] deal with actual application of academic of staff selection using the opinion of experts to be applied into a model of group decision - making by fuzzy ELECTRE. There are ten qualitative criteria for selecting the best candidate amongst five prospective applications.

Third group combines different decision making techniques and develops hybrid methods. Kaya and Kahraman [31] propose an e-banking website quality assessment methodology based on an integrated fuzzy AHP-ELECTRE approach. In the proposed methodology, the weights of the criteria are generated by a fuzzy AHP analysis. Next, fuzzy ELECTRE is used to assess the quality levels of the websites. In the third step, a fuzzy dominance relation approach is used to rank the alternatives. Kaya and Kahraman [32] propose an environmental impact assessment methodology based on an integrated fuzzy AHP-ELECTRE approach in the context of urban industrial planning. In the proposed methodology the criteria weights are generated by a fuzzy AHP procedure. A fuzzy outranking methodology, fuzzy ELECTRE is used to assess the environmental impact generated by the six different industrial districts which are predicted to shape the future industrial structure of Istanbul metropolitan area. Finally, a fuzzy dominance relation (FDR) methodology is used to rank the alternatives from the most risky to the least. Fuzzy ELECTRE papers using other generalizations and extensions of fuzzy sets have also been published in the literature. Some of these papers which have been recently published are given in the following.

Wu and Chen [33] develop the intuitionistic fuzzy ELECTRE method for solving multicriteria decision-making problems. Atanassov's intuitionistic fuzzy set (A-IFS) characteristics are simultaneously concerned with the degree of membership, degree of non-membership, and intuitionistic index, and people can use A-IFS to describe uncertain situations in decision-making problems. The proposed method can also use imperfect or insufficient knowledge of data to deal with decision-making problems. Devi and Yadav [34] propose intuitionistic fuzzy ELECTRE for the selection of appropriate plant location under group decision-making environment to tackle uncertainty of the information provided by decision makers. The ratings of alternatives with respect to each criterion and the weights of each criterion are taken as linguistic terms further characterized by triangular intuitionistic fuzzy sets. Chen [35] develops an ELECTRE-based outranking method for multicriteria group decision-making within the environment of interval type-2 fuzzy sets. Along with considering the context of interval type-2 trapezoidal fuzzy numbers, the paper employs a hybrid averaging approach with signed distances to construct a collective decision matrix and proposes the use of ELECTRE-based outranking methods to analyze the collective interval type-2 fuzzy data. This paper provides additional approaches at the final selection stage to yield a linear ranking order of the alternatives. Chen et al. [36] develop a hesitant fuzzy ELECTRE I (HF-ELECTRE I) method and apply it to solve the MCDM problem under hesitant fuzzy environment. The new method is formulated using the concepts of hesitant fuzzy concordance and hesitant fuzzy discordance which are based on the given score function and deviation function, and employed to determine the preferable alternative. The randomly generated numerical cases are also investigated in the framework of the HF-ELECTRE I method. Furthermore, the outranking relations obtained in the HF-ELECTRE I method with those derived from the aggregation operator-based approach and the ELECTRE III and ELECTRE IV methods are discussed.

2.1.2. PROMETHEE

Other two outranking methods are PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) and ORESTE. PROMETHEE I considers a partial preorder while PROMETHEE II does a total preorder on the set of possible actions by Brans [37]. A few years later, Brans et al. [38] developed PROMETHEE III and PROMETHEE IV methods. PROMETHEE III ranks alternatives based on intervals whereas PROMETHEE IV can be used for continuous cases. Both PROMETHEE and ORESTE methods have been also extended under fuzziness. Fuzzy ORESTE has been improved only in some conference papers [39, 40]. In the following, a literature review for fuzzy PROMETHE method is given.

Figure 3 shows the number of published papers using fuzzy PROMETHEE over years.

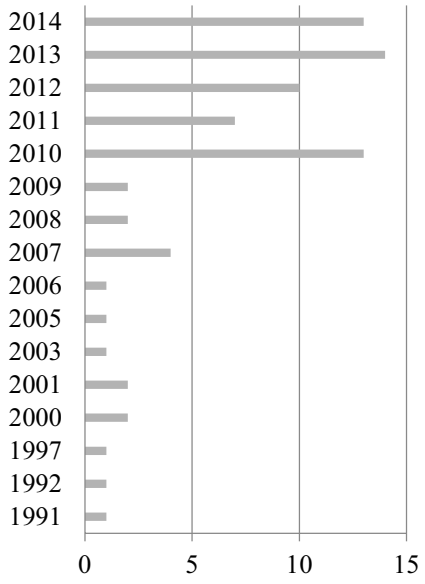

Figure 3. Published papers using fuzzy PROMETHEE over years.

Table 3 shows the journals most-publishing fuzzy PROMETHEE based articles.

Table 3. Journals that publish fuzzy PROMETHEE based articles

Journal Title	Total
Expert Systems with Applications	4
International Journal of Production Research	3
European Journal of Operational Research	3
International Journal of Uncertainty Fuzziness and Knowlege Based Systems	3
Journal of Intelligent and Fuzzy Systems	3
Analytica Chimica Acta	2

The fuzzy PROMETHEE based studies can be grouped into 3 groups. The studies that develop new fuzzy PROMETHEE methodologies or modify the existing approaches are in the first group. Goumas and Lygerou [41] develop fuzzy PROMETHEE using fuzzy input data, and apply this method to alternative energy exploitation schemes. Fernández-Castro and Jiménez [42] extent PROMETHEE method by using fuzzy integer linear programming where PROMETHEE III scorings are the objective function coefficients.

The studies that use the existing approaches in specific problem areas are the second group. Chou et al. [43] use fuzzy PROMETHEE in order to evaluate suitable ecotechnology method. Chen et al. [44] evaluate potential suppliers for outsourcing information systems with fuzzy PROMETHEE. Third group combines different decision making techniques with PROMETHEE and develops hybrid methods. Rao and Patel [45] integrate AHP and PROMETHEE under fuzziness for solving manufacturing problems. Yilmaz and Dagdeviren [46] combine fuzzy PROMETHEE and zero-one goal programming methods and apply this method for equipment selection.

Figure 4 presents the subject areas of the examined papers using fuzzy PROMETHEE.

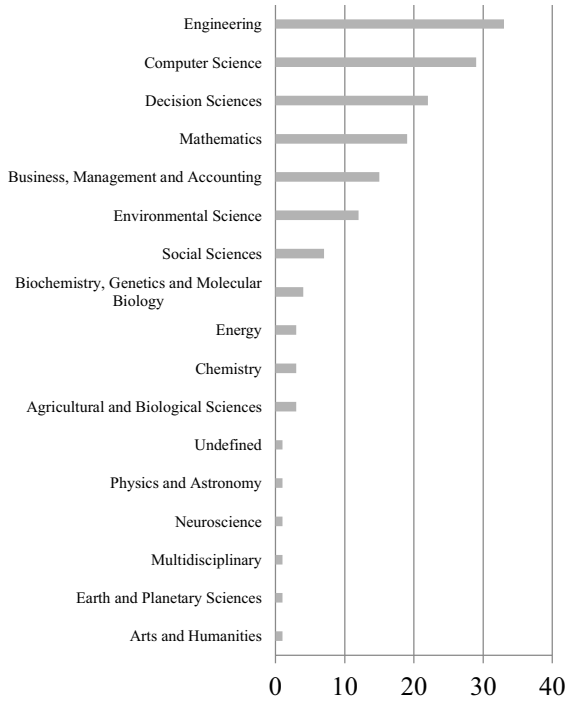

Figure 4. Subject areas of the examined papers using fuzzy PROMETHEE.

Table 4 shows the most influential articles on fuzzy PROMETHEE including their authors and cited times.

Table 4. Most influential articles on fuzzy PROMETHEE

Reference	Publication Year	Cited times
Goumas and Lygerou [41]	2000	135
Geldermann et al. [47]	2000	122
Araz et al. [48]	2007	80
Bilsel et al. [49]	2006	50
Tuzkaya et al. [50]	2010	24
Chou et al. [43]	2007	21

The authors S. Kokot (with 4 publications) from Queensland University of Technology, C. Kahraman (with 4 publications) from Istanbul Technical University, Y.C. Hu from Chung Yuan Christian University (with 3 publications), M. Ilangkumaran (with 3 publications) from K. S. Rangasamy College of Technology, G. Tuzkaya (with 3 publications) from Marmara University, and G. Achari (with 2 publications) from University of Calgary are the most productive researchers on fuzzy PROMETHEE.

2.2. *Distance based methods*

2.2.1. Fuzzy VIKOR

The acronym VIKOR stands for VIsekriterijumska optimizacija i KOmpromisno Resenje (Multicriteria Optimization and Compromise Solution). VIKOR, developed by Opricovic [51] is a technique which deals with multicriteria decision making problems that contain criteria with different units and that can be conflicting. The compromise solution is determined as a ranking index based on the particular measure of ‘‘closeness’’ to the ‘‘ideal’’ solution and the agreement established by mutual concessions [52].

The first paper that proposes to use fuzzy inputs with VIKOR method was published in 2002 [53]. Later, Opricovic [54] proposes a fuzzy extension of VIKOR to find a fuzzy compromise solution. With the proposed multicriteria decision making problems, in a fuzzy environment where both criteria and weights, could be fuzzy sets can be solved. In the method imprecise numerical quantities are defined by triangular fuzzy numbers.

A literature review for fuzzy VIKOR using SCOPUS gives 964 published papers (all fields). Among these, 117 papers mention fuzzy VIKOR in “article title, abstract, or keywords” and 56 papers in their titles. The numbers of articles published with respect to the years are shown in Figure 5.

In one of the recent studies, Chang [52] proposes using fuzzy VIKOR method to provide a systematic process for evaluating hospital service quality. In this approach the uncertainty, subjectivity and vagueness are addressed with linguistic variables which are represented as triangular fuzzy numbers. The approach uses fuzzy VIKOR method to consolidate the service quality performance ratings of the feasible alternatives. In the application of the method, the authors used 33 evaluation criteria and five medical centers in Taiwan. The assessment is accomplished by 18 evaluators from various fields of medical industry. The results of the study reveals that the service quality of private hospitals is better than public hospitals. In another recent study, Vinodth et al. [55] use fuzzy based VIKOR approach for concept selection for fit manufacturing which is a competitive manufacturing paradigm that includes lean and agile systems coupled with sustainable benefits. In the study concept selection is formulated as a multicriteria decision model with 20 criteria and four alternative concepts.

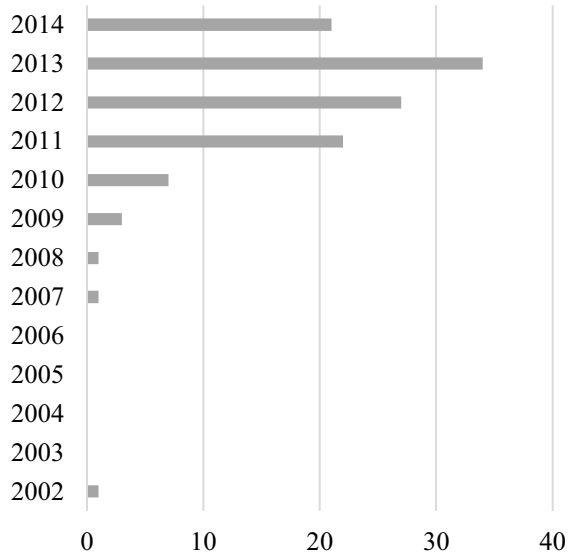

Figure 5. Fuzzy VIKOR Studies based on years.

Fuzzy VIKOR based studies have been published in various journals, the leading journals that publish articles in this area are given in Table 5.

Table 5. Journals that publish fuzzy VIKOR based articles

Journal Title	Total
Expert Systems with Applications	14
Applied Mathematical Modelling	6
Journal of Intelligent and Fuzzy Systems	4
Economic Computation and Economic Cybernetics Studies and Research	3
International Journal of Information Technology and Decision Making	2

The fuzzy VIKOR based studies can be grouped into 3 groups. The first group develops new fuzzy VIKOR methodologies or modifies the existing approaches:
Mousavi et al. [56] propose a new fuzzy grey multicriteria group decision-making method with uncertain information. The method uses linguistic terms using trapezoidal fuzzy numbers to provide the weights of the criteria and performance rating of alternatives. The method utilizes a grey relational analysis to investigate the extent of connections between two alternatives and a new ranking index is developed to obtain a compromise solution and to determine the best alternative in order to solve complex decision problems. Zhao et al. [57] extend the fuzzy VIKOR method using interval-valued intuitionistic fuzzy environment. The authors also propose a fuzzy cross-entropy approach to state the discrimination measure between optional and optimal interval-valued intuitionistic fuzzy numbers. Devi [58] propose extending VIKOR method using intuitionistic fuzzy sets. In the proposed methodology, the alternative ratings and criteria weights are represented as triangular intuitionistic fuzzy sets. The authors apply the proposed method to a robot selection problem for material handling task.

Second group uses the existing approaches in a specific problem area. Chang [52] uses fuzzy VIKOR method to consolidate the service quality performance ratings of five medical centers in Taiwan. The evaluation model is composed of 33 criteria and a group of evaluators assess the alternatives. Ebrahimnejad et al. [59] focus on risk ranking in mega projects. The authors use fuzzy VIKOR, fuzzy TOPSIS and fuzzy LINMAP on risk ranking problem and compare the results. Buyukozkan et al. [60] use fuzzy VIKOR to aid decision makers to identify the most appropriate knowledge management tool. The authors use the method for group decision making where the assessments are done using linguistic terms.

Third group combines different decision making techniques with VIKOR and develops hybrid methods. Aydin and Kahraman [61] use fuzzy VIKOR for the problem of bus selection for public transportation using. The problem includes several conflicting factors which are economic, social, and technological factors. A four levels hierarchy is established, and three experts are utilized for assessing the pairwise comparison matrices. The weights of the criteria are determined by fuzzy AHP and then the alternatives are ranked by fuzzy VIKOR. Oztaysi and Surer [62] utilize fuzzy AHP and fuzzy VIKOR for measuring the performance of supply chains. The authors build a performance measurement model based on SCOR Framework which is the basis for supply chain management. The proposed method fuzzy AHP is used to determine the weights of 16 criteria and fuzzy VIKOR is used to find the final performance score of the supply chain. Tadic et al. [63] focus on city logistics concept selection and develop a hybrid methodology containing fuzzy DEMATEL, fuzzy ANP and fuzzy VIKOR. In the proposed methodology fuzzy DEMATEL and fuzzy ANP is used to determine the weights of the criteria and fuzzy VIKOR is used to determine the final decision.

Fuzzy VIKOR method has been used in different areas. These areas can be categorized as follows: Computer science, engineering, mathematics, business management and accounting, decision sciences, environmental science, social sciences, agricultural and biological sciences, energy, biochemistry genetics and molecular biology, earth and planetary sciences, materials science, medicine, physics and astronomy, arts and humanities (see Figure 6). Especially in the computer science and engineering areas the method has been widely used.

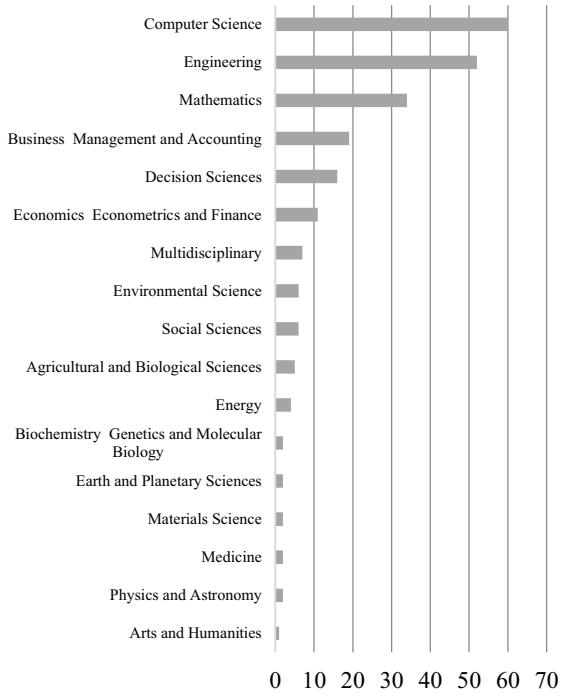

Figure 6. Fuzzy VIKOR Studies based on areas.

Authors R. Tavakkoli-Moghaddam (with 7 publications) from Islamic Azad University, S.F. Mousavi (with 6 publications) from Tarbiat Modares University and C. Kahraman (with 5 publications) from Istanbul Technical University are the most productive researchers in this field.

The most influential articles in this field are defined based on the total citation counts. Table 6 gives the most cited 20 articles in this field.

Table 6. Most influential articles on fuzzy VIKOR

Reference	Publication Year	Cited times
Opricovic and Tzeng [53]	2002	139
Sanayei et al. [64]	2010	112
Wu et al. [65]	2009	83
Kaya and Kahraman [66]	2010	79
Chen and Wang [67]	2009	64
Buyukozkan and Ruan [68]	2008	62
Shemshadi et al. [69]	2011	47
Opricovic [70]	2011	39
Kuo and Liang [71]	2011	35
Devi [58]	2011	33
Kaya and Kahraman[72]	2011	27
Vahdani et al. [73]	2010	26
Liu et al. [74]	2012	25
Girubha and Vinodh[75]	2012	25
Wu et al. [76]	2010	25
Bazzazi et al[77]	2011	23
Yalcin et al. [78]	2012	20
Liu and Wang [79]	2011	18
Ebrahimnejad et al. [80]	2012	17
Zhang N., Wei G.[81]	2013	15

Fuzzy VIKOR papers using other generalizations and extensions of fuzzy sets have also been published in the literature. Some of these papers which have been recently published are given in the following. Zhang and Wei [81] is one of the initial papers that propose an extension of VIKOR with hesitant fuzzy sets. The authors apply the method to a numerical case study about project selection with five experts and compared the results with TOPSIS method. Liao and Xu [82] develop hesitant normalized Manhattan Lp—metric, the hesitant fuzzy group utility measure, the hesitant fuzzy individual regret measure, and the hesitant fuzzy compromise measure. Based on these new definitions the authors propose a new hesitant fuzzy VIKOR method. The authors present the effectiveness of the method by a numerical case study about the service quality among domestic airlines. Wei and Zhang [83] focus on MCDM problems with inter-dependent or interactive criteria and preference of decision makers. The authors extend VIKOR method with Shapley value-based Lp-metric to deal with these correlative MCDM problems under hesitant fuzzy environment. The authors also compare the proposed method with TOPSIS approach on a numerical example. In recent papers, VIKOR method has been extended using intuitionistic fuzzy numbers. Park et al. [84] focus on dynamic intuitionistic fuzzy multiattribute decision making (DIF-MADM) problems. The authors propose two new operators namely dynamic intuitionistic fuzzy weighted geometric (DIFWG) operator and uncertain dynamic intuitionistic fuzzy weighted geometric (UDIFWG) operator. Based on these operators procedures for solving DIF-MADM problems where all evaluations are expressed in intuitionistic fuzzy numbers or interval-valued intuitionistic fuzzy numbers, which are collected at different periods. Wan et al. [85] focus on multicriteria group decision making using triangular intuitionistic fuzzy numbers. After developing triangular intuitionistic fuzzy weighted average (TIFNs) operator, the authors extend VIKOR method using triangular intuitionistic fuzzy sets. The authors also applied the method to personnel selection example to show the effectiveness of the method.

2.2.2. Fuzzy TOPSIS

The acronym TOPSIS stands for "Technique for Order Preference by Similarity to Ideal Solution". The initial TOPSIS approach is developed by Hwang and Yoon [86]. The main idea of the method is to choose alternative that have the shortest distance from the positive-ideal solution and the longest distance from the negative-ideal solution. A similarity index (or relative closeness coefficient) is calculated. This similarity index shows the distance to the positive-ideal solution and the remoteness from the negative-ideal solution. After this process, the alternative with the maximum relative closeness coefficient that considers the similarity to the positive-ideal solution as well as negative-ideal solution is selected.

Chen and Hwang [87] transform Hwang and Yoon's [86] method to fuzzy cases, and develop fuzzy TOPSIS method. Fuzzy TOPSIS method is widely used in literature. A literature review for fuzzy TOPSIS using SCOPUS gives 4,010 published papers (all fields). Among these, 739 papers mention fuzzy TOPSIS in "article title, abstract, or keywords" and 256 papers in their titles. The initial studies in this area dates back to 1993. After 2006 usage of fuzzy TOPSIS approaches is dramatically increased (see Figure 7). In 2013, 154 articles use this approach.

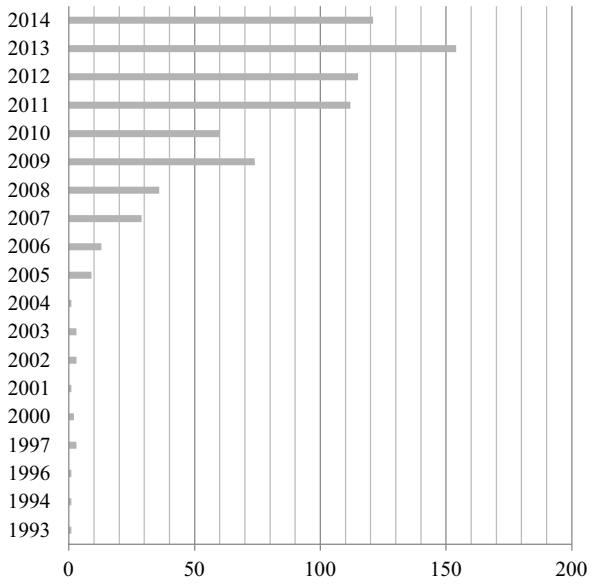

Figure 7. Fuzzy TOPSIS Studies based on years.

The fuzzy TOPSIS based studies can be grouped into 3 groups. The first group develops new fuzzy TOPSIS methodologies or modify the existing approaches: Ye and Li [88] modify TOPSIS method by using possibility theory. The evaluations of the decision-makers are done via triangular fuzzy numbers (TFNs). The integrated relative closeness coefficient of each alternative is computed via the possibilistic mean value matrix and the possibilistic standard deviation matrix. Kahraman et al. [89] develop a fuzzy hierarchical fuzzy TOPSIS method for the multicriteria evaluation of the industrial robotic systems. This method considers the hierarchy among attributes. The proposed approach is applied to industrial robotic system selection problem. Chen and Wei [90] extends Chen and Hwang's [87] methodology and describes the rating of each alternative and the weight of each criterion by linguistic terms which can be expressed in triangular fuzzy numbers. The distance between two triangular fuzzy numbers is calculated via a vertex method.

Second group uses the existent approaches in a specific problem area. Kannan et al. [91] use fuzzy TOPSIS for ranking green suppliers for a Brazilian electronics company. Wang [92] evaluates financial performance of Taiwan container shipping companies with fuzzy TOPSIS. Chu [93] uses fuzzy TOPSIS model for solving the facility location selection problem.

Third group combines different decision making techniques and develops hybrid methods. Mandic et al. [94] develop an integrated fuzzy multicriteria model for assessing financial performance of banks. Fuzzy AHP is utilized for evaluating the weights. A fuzzy TOPSIS method is used for evaluating the banks. Zhang and Lu [95] develop an integrated fuzzy group decision-making method in order to deal with the fuzziness of preferences of the decision-makers. The weights of the criteria are defined as crisp values and gathered by pairwise comparisons. The preferences of the decision-makers are triangular fuzzy numbers (TFNs). Tsaura et al. [96] use a hybrid approach for evaluating evaluate the service quality of airline. AHP method is used for obtaining criteria weights and TOPSIS method is used for ranking.

Fuzzy TOPSIS based studies have been published in various journals, the leading journals that publish articles in this area are given in Table 7.

Table 7. Journals that publish fuzzy TOPSIS based studies

Journal	Total
Expert Systems with Applications	87
Applied Soft Computing Journal	26
Applied Mathematical Modelling	17
Journal of Intelligent and Fuzzy Systems	16
International Journal of Advanced Manufacturing Technology	16

Fuzzy TOPSIS method has been used in different areas. These areas can be categorized as follows: Engineering, Computer Science, Mathematics, Business, Management and Accounting, Decision Sciences, Environmental Science, Multidisciplinary, Earth and Planetary Sciences, Economics, Econometrics and Finance, Social Sciences, Agricultural and Biological Sciences, Energy, Materials Science, Biochemistry, Genetics and Molecular Biology, Medicine Physics and Astronomy, Arts and Humanities, Chemical Engineering and Chemistry (Figure 8). Especially in the engineering and computer science areas the method has been widely used.

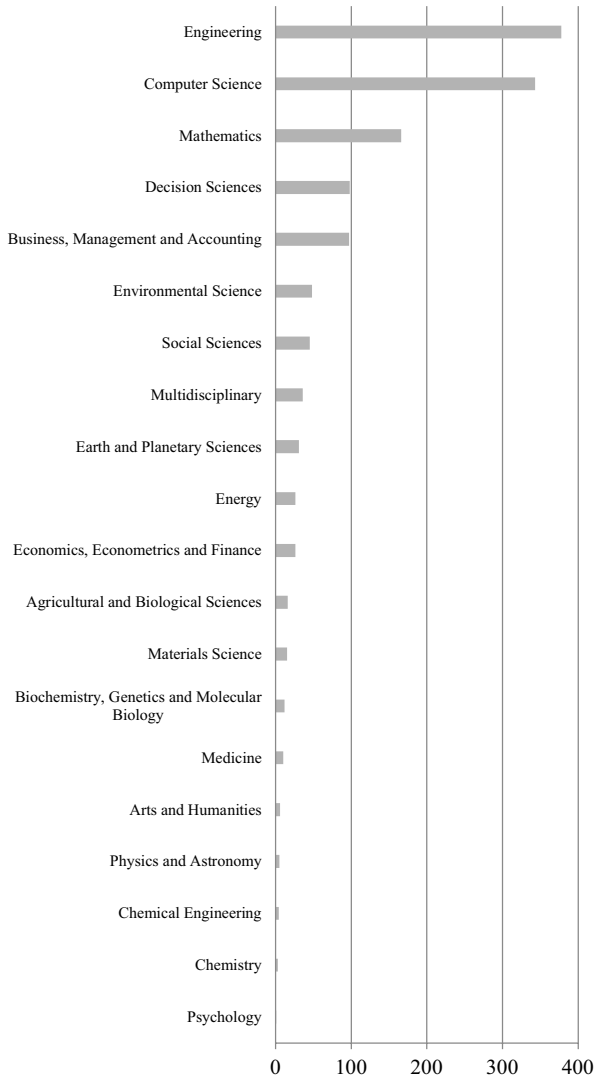

Figure 8. Fuzzy TOPSIS Studies based on areas.

Authors C. Kahraman (with 21 publications) from İstanbul Technical University, R. Tavakkoli-Moghaddam (with 9 publications) from Islamic Azad Universtiy, C.M. Liu (with 7 publications) from Feng Chia University, D. Li (with 7 publications) from Fuzhou University, B. Vahdani (with 7 publications) from Islamic Azad Universiy, M. Tavana (with 7 publications) from La Salle University, M.A. Abo-Sinna (with 7 publications) form Princess Nora Bint Abdul Rahman University and G. Buyukozkan (with 7 publications) from Galatasaray University are the most productive researchers in this field.

The most influential articles in this field are defined based on the total citation counts. Table 8 gives the most cited 20 articles in this field.

Table 8. Most influential articles on fuzzy TOPSIS

References	Publication Year	Cited times
Wang et al. [97]	2006	238
Boran et al. [98]	2009	219
Yang and Hung [99]	2007	150
Dagdeviren et al. [100]	2009	140
Yong [101]	2006	130
Wang et al. [102]	2009	126
Onut and Soner [103]	2008	120
Chu and Lin [104]	2003	117
Wang and Lee [105]	2007	115
Chu [106]	2002	109
Onut et al. [107]	2009	104
Chu [93]	2002	101
Buyukozkan et al. [108]	2008	100
Wang and Lee [109]	2009	99
Ashtiani et al. [110]	2009	84
Chen and Tsao [111]	2008	83
Bottani and Rizzi [112]	2006	82
Deng and Chan [113]	2011	80
Braglia et al. [114]	2003	80
Kahraman et al. [89]	2007	79

In recent papers, fuzzy TOPSIS method has been extended using intuitionistic fuzzy numbers, hesitant fuzzy sets and type-2 fuzzy sets.

Yue [115] proposes an extended fuzzy TOPSIS for group decision making problems in an intuitionistic fuzzy environment. First the individual evaluations are collected with this method. Then, these individual evaluations are converted into the group decision of alternatives. Joshi and Kumar [116] propose an intuitionistic fuzzy TOPSIS method for portfolio selection problem. The method uses intuitionistic fuzzy entropy and conversion theorem to convert fuzzy sets to intuitionistic fuzzy sets

Cevik Onar et al. [117] develop a hybrid approach for evaluating strategic decisions. In this model the weights of the factors are defined by interval type-2 AHP and strategies are evaluated via hesitant fuzzy TOPSIS using the determined weights. Liu and Rodriguez [118] modify TOPSIS method by using hesitant fuzzy sets. In this model the hesitant fuzzy linguistic term sets are defined as fuzzy envelope. The applicability of the model is shown via supplier selection problem.

Kahraman et al. [119] integrate pairwise comparisons approach with fuzzy TOPSIS in order to deal with supplier selection problems where the decision makers are hesitant in their decisions. Xu and Zhang [120] extend TOPSIS method for evaluating alternatives, where decision makers are hesitant and the information on attribute weights is incomplete. Celik et al. [121] propose a hybrid model for defining satisfaction level of public transportation. This method combines interval type-2 fuzzy TOPSIS and Grey Relational Analysis (GRA). Chen and Lee [122] propose an interval type-2 fuzzy TOPSIS. The authors claim that using Type-2 fuzzy sets increase the flexibility of decision making process. Yavuz et al. [123] propose a hierarchical hesitant fuzzy linguistic multicriteria decision making model for alternative fuel vehicles. The distances to negative and positive ideal solutions are defined in order to select alternative fuel vehicle.

2.3. *Pairwise comparisons based methods*

2.3.1. Fuzzy AHP Methods

Analytic Hierarchy Process (AHP) is initially proposed by Saaty [124] as a structured approach used for decision making in complex problems. AHP organizes the decision making criteria as a hierarchy and aims quantifying relative priorities for a given set of alternatives based on the decision makers' pairwise judgments. AHP also stresses the consistency of the comparison of alternatives and has the ability to detect and incorporate inconsistencies inherent in the decision making process.

In the original method, decision makers' evaluations are represented as crisp numbers. However, in cases where decision makers cannot express the evaluations by crisp numbers, fuzzy logic can be used which provides a mathematical strength to capture the uncertainties associated with human cognitive process [125]. There are various fuzzy extension proposals of AHP in the literature. Laarhoven and Pedrycz [126] propose the first algorithm in fuzzy AHP by using triangular fuzzy membership functions. Buckley [127] extends AHP with trapezoidal fuzzy numbers and used the geometric mean method to derive fuzzy weights and performance scores. Chang [128] suggests using extent analysis method for the synthetic extent values of the pairwise comparisons by utilizing triangular fuzzy numbers. In one of the recent studies Zeng et al. [129], propose using arithmetic averaging method to get performance scores and extend the method with different scales contains triangular, trapezoidal, and crisp numbers.

A literature review for fuzzy AHP using SCOPUS gives 8,284 published papers (all fields). Among these, 1,792 papers mention fuzzy AHP in "article title, abstract, or keywords" and 451 papers in their titles. Yearly distribution of papers using fuzzy AHP is given in Figure 9.

As the number of publications imply, fuzzy AHP has been used as a research method in various areas. In one of the recent studies, Rezaei et al. [130] focus on supplier selection in the airline retail industry. The authors propose a two-phased methodology, in the first phase conjunctive screening method is used to reduce the initial set of potential suppliers. In the second phase, a fuzzy AHP is used to evaluate alternative suppliers against the main criteria and sub-criteria. The proposed approach is applied to one of the largest airlines in Europe, KLM Royal Dutch Airlines. In another recent study, Ozgen and Gulsun [131] focus on multi-facility location problem considering both quantitative and qualitative factors To this end the authors propose using possibilistic linear programming approach and fuzzy AHP to optimize two objective functions *minimum cost* and *maximum qualitative factors benefit*. The authors also present a numerical example with a four-stage supply chain case study which contains suppliers, plants, distribution centers and customers supply chain network.

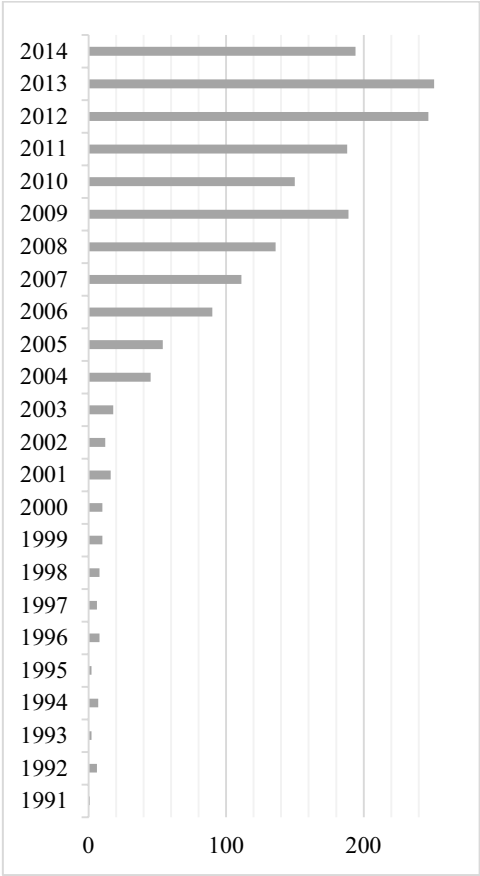

Figure 9. Fuzzy AHP Studies based on years.

Fuzzy AHP based studies have been published in various journals, the leading journals that publish articles in this area are given in Table 9.

Table 9. Journals that publish fuzzy AHP based studies

Journal Title	Total
Expert Systems with Applications	99
Computer Integrated Manufacturing Systems	28
International Journal of Production Research	27
European Journal of Operational Research	19
Fuzzy Sets and Systems	18

The fuzzy AHP based studies can be grouped into 3 groups. The first group develops new fuzzy AHP methodologies or modifies the existing approaches:
Jalao et al. [132] propose a stochastic AHP method to overcome the problem of bounded rationality. The authors underline that decision makers have limited cognitive powers in specifying their preferences over multiple pairwise comparisons. In the proposed method a beta distribution is used to model the varying stochastic preferences of decision maker. The method-of-moments methodology is used to fit the varying stochastic preferences into beta stochastic pairwise comparisons. A non-linear programming model is also proposed to maintain consistency of evaluations. Xu and Liao [133] extend fuzzy AHP into the intuitionistic fuzzy in order to handle problems where decision makers have some uncertainty in assigning preference values and evaluations. In the proposed method intuitionistic fuzzy numbers are used for expert evaluations. The authors develop a technique to check the consistency of an intuitionistic preference relation and a novel normalizing rank summation method to derive the priority vector of an intuitionistic preference relation. Deng et al. [134] focus on supplier selection problem and extend AHP method with D Numbers which is identified as a new effective and feasible representation of uncertain information. In the proposed method the pairwise comparison are filled with D numbers and all other steps of the methodology is extended accordingly. The authors also provide an illustrative example on supplier selection to demonstrate the effectiveness of the method.

Second group uses the existing approaches in a specific problem area. In the literature fuzzy AHP method is used in various application areas. Wang et al. [135] use fuzzy AHP in leisure travel industry. The author use fuzzy AHP to identify the main factors motivating cruise lines to select specific ports of call. In another study, Gim and Kim [136] apply fuzzy AHP to evaluate five hydrogen storage systems. In the decision model the authors consider weight efficiency, volume efficiency, system cost, energy efficiency, cycle life, refueling time, safety and infrastructure. The result of the study shows that compressed gas hydrogen ranks the highest in classification in Korea. Calabrese et al. [137] propose using fuzzy AHP to analyze the impact of intellectual capital components on a company value creation process. The authors model the decision problem with two criteria, six sub-criteria and seven alternatives. The authors also present a numerical application of the problem in an ICT company.

Third group combines different techniques with fuzzy AHP and develops hybrid methods. Jakhar and Barua [138] focus on supply chain performance. The authors integrate structural equation modeling and fuzzy AHP to propose a comprehensive evaluation tool and decision model to measure supply chain performance and guide for further improvements. In the proposed

model SEM is used to determine the weights of five criteria and 19 sub-criteria of the performance evaluation system, and the fuzzy AHP is used to determine the relative weights of decision-making levels with respect to each criteria and sub-criteria. In another study, Cho and Lee [139] focus on factors that affect commercialization of new technology products. In the study the authors integrate Delphi [140] and fuzzy AHP methods. First four decision areas are determined based on the literature review and Delphi method. Then, fuzzy AHP method is applied for prioritization of sixteen success factors. In a different area, Kaya et al. [141] apply a hybrid decision making method for public transportation policy selection. The authors propose a two-phased multicriteria methodology to select the best investment alternative for public transportation. In the first phase, selection among transportation types is made using axiomatic design [142] and in the second phase, a selection among transportation modes of the selected transportation type is made using fuzzy AHP. The authors also present a case study for Istanbul.

Fuzzy AHP method has been used in different areas. These areas can be categorized as follows: Engineering, computer science, mathematics, environmental science, business management and accounting, decision sciences, earth and planetary sciences, social sciences, energy, agricultural and biological sciences, multidisciplinary, materials science, physics and astronomy (Figure 10). Especially in the engineering and computer science areas the method has been widely used.

Authors C. Kahraman (with 42 publications) from Istanbul Technical University, G.H. Tzeng (with 17 publications) from National Taipei University, G. Buyukozkan, (with 12 publications) from Galatasaray University, D. Ruan from Belgian Nuclear Research Centre and T.C. Wang (with 10 publications) from I-Shou University are the most productive researchers in this field.

The most influential articles in this field are defined based on the total citation counts. Table 10 gives the most cited 20 articles in this field.

Figure 10. Fuzzy AHP Studies based on areas.

Table 10. Most influential articles on fuzzy AHP

References	Publication Year	Cited times
Chang [128]	1996	835
Chan and Kumar [143]	2007	359
Tsaur et al. [144]	2002	298
Kahraman et al.[145]	2006	266
Kahraman et al. [146]	2004	262
Tzeng et al. [147]	2007	255
Deng [148]	1999	240
Kahraman et al. [149]	2003	229
Cheng [150]	1997	203
Zhu and Chow [151]	1997	197
Leung and Cao [152]	2000	196
Kulak and Kahraman [153]	2005	193
Lee et al. [154]	2008	171
Kwong and Bai [155]	2002	166
Kwong and Bai [156]	2003	161
Chen and Tzeng [157]	2004	159
Cheng et al. [158]	1999	157
Bozdag et al. [159]	2003	150
Dagdeviren et al. [100]	2009	140
Chan et al. [160]	2008	139

Fuzzy AHP papers using other generalizations and extensions of fuzzy sets have also been published in the literature. While there are no applications AHP using hesitant fuzzy sets, integration of type-2 fuzzy sets with fuzzy AHP has some initial applications. Kahraman et al. [161] extend existing fuzzy AHP literature with interval type-2 fuzzy sets. The authors explain the extended procedure for the proposed method also propose a new defuzzification method for interval type-2 fuzzy sets. In order to show the effectiveness of the method a numerical case is given for a supplier selection problem. In another study, Onar et al.[117] focus on strategy selection problem and use Type-2 fuzzy AHP and hesitant TOPSIS methods. In the study, type-2 fuzzy AHP is used to determine the weights of the criteria and hesitant TOPSIS is used to select among the strategic decisions. Abdullah and Najib [162] also propose a new fuzzy AHP method using interval type-2 fuzzy sets. In the proposed method, linguistic evaluations are represented as trapezoidal interval type-2 fuzzy sets and the authors propose a rank value method for normalizing upper and lower memberships of these sets. The authors also represent a numerical example in work safety evaluation problem. In the literature there are various papers that use fuzzy AHP with intuitionistic fuzzy numbers. Wu et al. [163] focus on multicriteria decision making with interval-valued intuitionistic fuzzy preference relations (IVIFPRs). The authors propose a novel interval score function and a prioritization method. The authors also investigate an interval-valued intuitionistic fuzzy AHP method for multicriteria decision making (MCDM) problems. Abdullah and Najib [164] propose a new method which intuitionistic fuzzy sets (IFS) with AHP method. To this end the authors also propose a new preference scale which considers the degree of hesitation of IFS in expressing the conversion of consistency to a triangular intuitionistic fuzzy numbers. In order to apply the method in group decision making, the intuitionistic fuzzy weighted averaging (IFWA) is utilized to aggregate the matrix assessment of the decision. The authors apply the proposed method to three problems to show the effectiveness of the method. In another study, Xu and Lia [133] propose a new intuitionistic fuzzy AHP (IFAFP) in which preferences are represented by intuitionistic fuzzy values and thus can handle more complex problems. The authors also propose a new way to check the consistency of an intuitionistic preference relation and then improve the inconsistent intuitionistic preference relation without the participation of the decision maker. The authors also propose a novel normalizing rank summation method to derive the priority vector of an intuitionistic preference relation.

2.3.2. Fuzzy ANP Methods

ANP method is a generalization of AHP method, and developed by Saaty [165]. Similar to AHP method in ANP method pairwise comparisons are used. On the other hand, in ANP method the factors are not independent of each other. In ANP framework a relationship among elements in the same cluster is called as inner dependence (loops). An arc from one cluster to another refers to outer dependency. An outer-dependency between two clusters in both directions is called feedback [165]. The problem cannot be structured as hierarchical structure due to the loops and feedbacks. Steps of ANP method can be defined as structuring, modeling and analyzing. Selecting the problem and identifying the criteria is the structuring step. In the modeling step questions based on pairwise comparisons are asked to the experts. The analysis step includes calculating group judgments and finding the priorities.

Fuzzy ANP Method is widely used in the literature. A literature review for fuzzy ANP using SCOPUS gives 1,542 published papers (all fields). Among these, 206 papers mention fuzzy ANP in their “article title, abstract, or keywords” and 53 papers in their titles. The initial studies in this area dates back to 2003. After 2009 usage of fuzzy ANP approaches is dramatically increased (see Figure 11). In 2013, 43 articles used this approach.

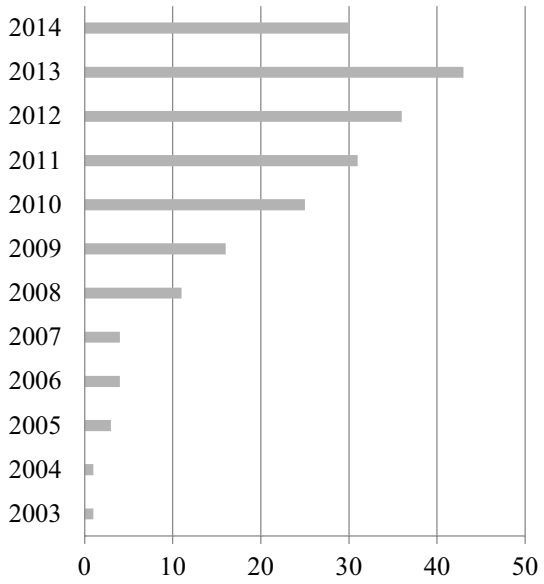

Figure 11. Fuzzy ANP Studies based on years.

The fuzzy ANP based studies can be grouped into 3 groups. The first group develops new fuzzy ANP methodologies or modifies the existing approaches: Büyüközkan et al. [166] develop a fuzzy ANP, in order to prioritize design requirements by taking into account the degree of the interdependence between the customer needs and design requirements. Onut et al. [107] develop a fuzzy ANP method and combined this method with fuzzy TOPSIS for evaluating suppliers. Triangular fuzzy numbers are used in all pairwise comparison matrices. Then, fuzzy TOPSIS methodology with the obtained weights is applied to rank the alternatives.

Second group uses the existent approaches in a specific problem area. Kahraman et al. [145] use an integrated framework based on fuzzy-QFD and a fuzzy optimization model for determining the product technical requirements. Fuzzy ANP is used for obtaining the coefficients of the objective function. Pourjavad and Shirouyehzad [167] use fuzzy ANP method for evaluating performance of manufacturing systems. Manufacturing lines in a facility are compared based on quality, product, maintenance and cost criteria. Li et al. [168] utilize fuzzy ANP for evaluating strategic leadership. The evaluation process enables selecting appropriate candidates for promotion. Oztaysi et al. [169] rank green energy alternatives with fuzzy ANP. Technical, economical, and environmental criteria are used for evaluating green energy alternatives in Turkey.

Third group combines different decision making techniques and develops hybrid methods.
Senvar et al. [170] develop a fuzzy DEMATEL and fuzzy ANP based hybrid approach for evaluation supply chain performance. Fuzzy ANP is used for dealing with dependence and feedback among measurement criteria. Tadic et al. [171] develop a hybrid model that combines fuzzy DEMATEL, fuzzy ANP and fuzzy VIKOR methods for city logistics concept selection.

Fuzzy ANP based studies have been published in various journals, the leading journals that publish articles in this area are given in Table 11.

Table 11. Journals that publish fuzzy ANP based studies

Journal	Total
Expert Systems with Applications	32
Computers and Industrial Engineering	8
International Journal of Production Research	7
Applied Mathematical Modelling	6

Fuzzy ANP method has been used in different areas. These areas can be categorized as follows (see Figure 12): Engineering, computer science, decision sciences, mathematics, business, management and accounting, social sciences, environmental science, economics, econometrics and finance, multidisciplinary, biochemistry, genetics and molecular biology, medicine, energy, agricultural and biological sciences, earth and planetary sciences, arts and humanities, materials science, chemical engineering, chemistry, health professions and psychology.

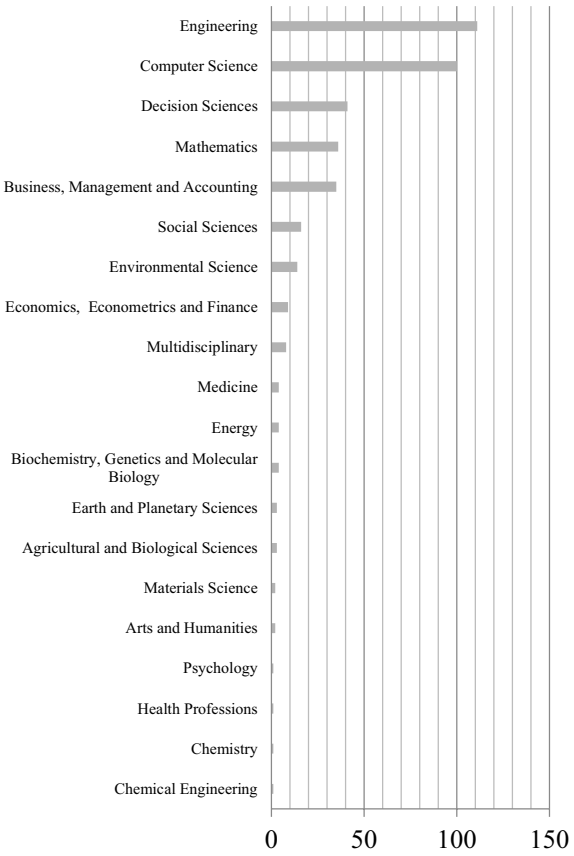

Figure 12. Fuzzy ANP Studies based on areas.

M.L. Tseng, (with 9 publications) from Shenyang Institute of Applied Ecology, C. Kahraman (with 7 publications) from Istanbul Technical University, G. H. G.H. Tzeng (with 7 publications) from National Taipei University, A.H.I. Lee (with 6 publications) from Chung Hua University, and M. Tavana (with 6 publications) from Universitat Paderborn are the most productive researchers in this field.

The most influential articles in this field are defined based on the total citation counts. Table 12 gives the most cited 20 articles in this field.

Table 12. Most influential articles on fuzzy ANP

References	Publication Year	Cited times
Kahraman et al.[145]	2006	266
Onut et al. [107]	2009	104
Yu and Tzeng [172]	2006	81
Tseng et al. [173]	2009	72
Ayag and Ozdemir [174]	2009	62
Dagdeviren et al. [175]	2008	62
Sipahi and Timor [176]	2010	61
Tuzkaya and Onut [177]	2008	59
Lin [178]	2009	53
Buyukozkan and Cifci [179]	2012	52
Ayag and Ozdemir [180]	2007	52
Yuksel and Dagdeviren [181]	2010	50
Vinodh et al. [182]	2011	49
Promentilla et al. [183]	2008	45
Tseng [184]	2010	44
Tseng et al. [185]	2009	43
Chen et al. [186]	2008	43
Chen and Chen [187]	2010	42
Razmi et al. [188]	2009	39
Lin et al. [189]	2010	35
Wey and Wu [190]	2007	35

There is no study on fuzzy ANP using the extended fuzzy sets, including hesitant, type-2 and intutionistic fuzzy sets.

2.3.3. Fuzzy MACBETH

MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique) is a multicriteria decision making approach whose development was set in motion in the early 1990's by Bana e Costa and Vansnick [191].In subsequent years, this team expanded by the addition of J.-M. De Corte.

MACBETH is an interactive approach that allows a decision maker or a decision-advising group to evaluate alternatives by simply making qualitative comparisons regarding their differences of attractiveness in multicriteria analysis. Thus, what distinguishes MACBETH from the other multicriteria models is that it needs only qualitative judgments about the difference of attractiveness between two elements at a time, in order to generate numerical scores for the options in each criterion and to weight the criteria [192].

A literature review for fuzzy MACBETH using SCOPUS gives 199 published papers (all fields). Among these, only 3 papers mention fuzzy MACBETH

in “article title, abstract, or keywords” and 2 papers in their titles.

Dhouib [192] develops an extended version of MACBETH methodology to take into account the imprecise and linguistic assessments provided by a decision-maker by integrating the 2-tuple model dealing with non-homogeneous information data. The proposed fuzzy MACBETH method is applied to a real case related to the automobile tire waste. Ertay et al. [193] evaluate the renewable energy alternatives as a key way for resolving the Turkey's energy-related challenges because of the fact that Turkey's energy consumption has risen dramatically over the past three decades as a consequence of economic and social development. In order to realize this aim, they comparatively use MACBETH and AHP-based multicriteria methods for the evaluation of renewable energy alternatives under fuzziness.

MACBETH method has not yet been expanded to its fuzzy versions using Intuitionistic fuzzy sets, hesitant fuzzy sets, or type-2 fuzzy sets.

2.4. *Other Fuzzy Multiattribute Decision Making Methods*

DEMATEL (Decision Making Trial and Evaluation Laboratory) method was originally developed between 1972 to 1979 by the Science and Human Affairs Program of the Battelle Memorial Institute of Geneva, with the purpose of studying the complex and intertwined problematic group [194, 195]. It has been widely accepted as one of the best tools to solve the cause and effect relationship among the evaluation criteria. DEMATEL method is based on digraphs, which separate involved factors into cause group and effect group. The digraph may portray a basic concept of contextual relation among elements of a system, in which the values represent the strength of influence. The DEMATEL can convert the relationship between cause and effect factors into an intelligible structural model of the system. The DEMATEL can propose the most important criteria which affects other criteria [196].

Chang et al. [196] use fuzzy DEMATEL method to find influential factors in selecting the best suppliers. The fuzzy DEMATEL method evaluates supplier performance to find key factor criteria to improve performance and provides a novel approach of decision-making information in supplier selection. This research designs a fuzzy DEMATEL questionnaire sent to seventeen professional purchasing personnel in the electronic industry. Tadic et al. [171] develop a novel hybrid MCDM model that combines fuzzy DEMATEL, fuzzy ANP and fuzzy VIKOR methods. The model provides support to decision makers when selecting the city logistics concept. Yeh and Huang [197] examine the key factors considered in determining the location of wind farms. DEMATEL and ANP approaches are applied to find the correlations among the dimensions and the relative weights of the criteria, respectively.

A literature review for fuzzy DEMATEL using SCOPUS gives 600 published papers (all fields). Among these, 103 papers mention fuzzy DEMATEL in “article title, abstract, or keywords” and 38 papers in their titles. Figure 13 shows the distribution of 103 papers over the years, which mention fuzzy DEMATEL in its title, abstract, or keywords.

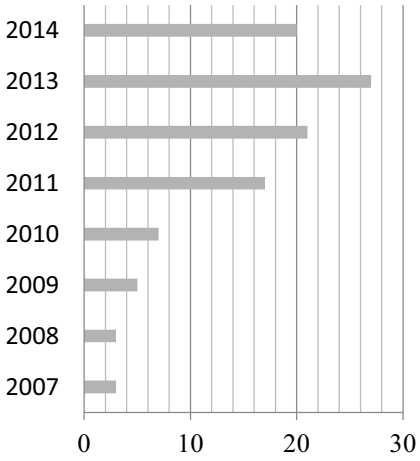

Figure 13. Fuzzy DEMATEL studies based on years.

Table 13 shows the journals most-publishing fuzzy DEMATEL based articles.

Table 13. Journals that publish fuzzy DEMATEL based articles

Journal	Total
Expert Systems with Applications	19
Applied Soft Computing Journal	8
Advances in Environmental Biology	3
Safety Science	3
International Journal of Operational Research	2

Figure 14 shows the fuzzy DEMATEL studies with respect to their interest areas.

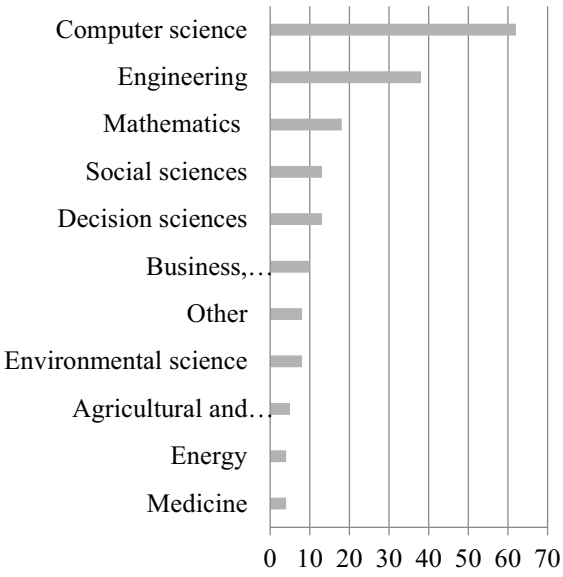

Figure 14. Fuzzy DEMATEL Studies based on areas.

Fuzzy DEMATEL papers using other generalizations and extensions of fuzzy sets have also been published in the literature. Some of these papers which have been recently published are given in the following.

Li et al. [198] propose a new method identifying the critical success factors (CSF). In this method, the evaluations of influencing factors in the form of intuitionistic fuzzy numbers (IFNs) are converted into basic probability assignments (BPA). Then Dempster-Shafer theory is adopted to combine group decision. By doing so, there is no need for defuzzification of IFNs, and DEMATEL is applied on each fused BPA to seek for a final result from different aspects. Nikjoo and Saeedpoor [199] propose a methodology based on DEMATEL technique which can deal with the causal relationships among factors to overcome this problem. Also, in order to embrace the vagueness of human's subjective judgments they take advantage of intuitionistic fuzzy sets (IFS) theory. Finally, they apply their methodology in one of the Iranian insurance company to determine the most important components of Strengths-Weakness-Opportunities-Threats (SWOT) matrix. Bokaei and Tarokh [200] extend the DEMATEL method based on the interval type-2 fuzzy sets to obtain the weights of criteria based on words. DEMATEL method has not been yet extended to obtain hesitant fuzzy DEMATEL method. Table 14 shows the most influential articles on fuzzy DEMATEL.

Table 14. Most influential articles on fuzzy DEMATEL

References	Publication Year	Cited times
Tzeng et al. [147]	2007	255
Wu and Lee [201]	2007	167
Lin and Wu [202]	2008	123
Liou et al. [203]	2008	59
Buyukozkan and Cifci [179]	2012	52
Tseng[204]	2009	52
Tseng[205]	2010	44
Chang et al. [196]	2011	43
Zhou et al. [206]	2011	32

G.H. Tzeng (with 13 publications) from National Taipei University, M.L. Tseng, (with 9 publications) from Shenyang Institute of Applied Ecology, Liou (with 5 publications) from National Taipei University of Technology, I.S. Chen (with 4 publications) from Trinity College Dublin, and J.K. Chen (with 4 publications) from Tamkang University are the most productive researchers on fuzzy DEMATEL.

Another technique that is used in fuzzy multiattribute decision making literature is fuzzy axiomatic design [142]. In the most cited study using this technique Kulak and Kahraman [153] focus on transportation company selection problem by utilizing fuzzy axiomatic design. In the proposed method, linguistic terms are used to define design and system ranges. The linguistic terms are later represented as triangular fuzzy sets and procedures of axiomatic design is applied to these sets. In another study, Büyüközkan et al. [207] propose a two phased approach for logistics tool selection problem. In the first phase the basic requirements are defined and the alternatives which cannot fulfill the threshold values are eliminated. In the second, the remaining alternatives are evaluated using fuzzy axiomatic design. Kulak et al. [208] use fuzzy axiomatic design for information technology selection using both tangible and intangible project selection factors.

Choquet integral is another technique used for fuzzy multiattribute decision making problems in which dependence between attributes exist. In one of the mostly cited study, Marichal [209] mathematically show that discrete Choquet integral is an appropriate tool for dealing with interacting criteria. Grabisch et al. [210] focus on usage of Choquet integral in multiattribute utility theory and investigates the possible capacity identification approaches. Choquet integral is also used in intuitionistic fuzzy sets. Xu [211] proposes a Choquet integral based operator for interval valued intuitionistic

fuzzy sets, which can take into the importance of the elements and correlations among the elements. Yang and Chen [212] extend the Choquet integral for linguistic 2-tuple in MCDM problems.

Data Envelopment Analysis is a method in operations research that can be used to determine the efficiency of decision making units [213]. However, in the literature there are some studies that use fuzzy DEA in multiattribute decision making problems. In one of the most cited studies Ertay et al. [214] integrate fuzzy DEA with AHP method for facility layout design which can handle both qualitative and quantitative data. In another study, Liu [215] develops a fuzzy DEA/AR method which can evaluate the performance of flexible manufacturing system alternatives where the input and output data can be fuzzy as well as crisp values. Wu [216] proposes an integrated technique using data envelopment analysis and fuzzy preference relations to rate decision alternatives. In the three step technique, first pairwise efficiency scores are computed using DEA, then these scores are used to construct the fuzzy preference relation and the consistent fuzzy preference relation, finally priority vector is determined using row wise summation.

3. Fuzzy Multiobjective Decision Making

Multiobjective Decision Making problems deal with the cases where there are more than one objective function to be optimized simultaneously. There are a priori methods where sufficient preference information is expressed before the solution process such as utility function method, lexicographic method and goal programming; posteriori methods which aim at producing all the Pareto optimal solutions such as genetic algorithms, particle swarm optimization and simulated annealing. There are also hybrid methods that combine multicriteria decision making with multiobjective decision making.

Fuzzy Multiobjective Decision Making (FMODM) problems deal with situations where there are imprecision and uncertainty in some parameters [217].
Fuzzy Multiobjective Decision Making Methods are widely used in literature. A literature review for Fuzzy Multiobjective Decision Making Methods using SCOPUS gives 1,651 published papers (all fields). Among these, 368 papers mention fuzzy Multiobjective Decision Making Methods in “article title, abstract, or keywords” and 256 papers in their titles. The initial studies in this area dates back to 1984. After 2006 usage of fuzzy FMODM approaches is dramatically increased (Figure 15). In 2013, 54 articles use this approach.

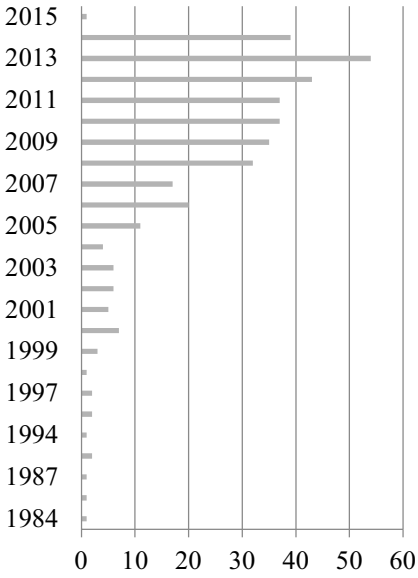

Figure 15. Distribution of the examined FMODM papers over the years.

FMODM based studies have been published in various journals, the leading journals that publish articles in this area are given in Table 15.

Table 15. Journals that publish FMODM based studies

Journal	Total
International Journal of Production Research	14
European Journal of Operational Research	12
Expert Systems with Applications	12
Computers and Industrial Engineering	10
Fuzzy Sets and Systems	9

FMODM methods have been used in different areas. These areas can be categorized as follows (Figure 16): Engineering, Computer Science, Mathematics Decision Sciences, , Business, Energy, Environmental Science, Social Sciences, Economics, Agricultural and Biological Sciences, Materials Science, Physcis and astronomy, Chemical Engineering, Biochemistry, Arts and Humanities.

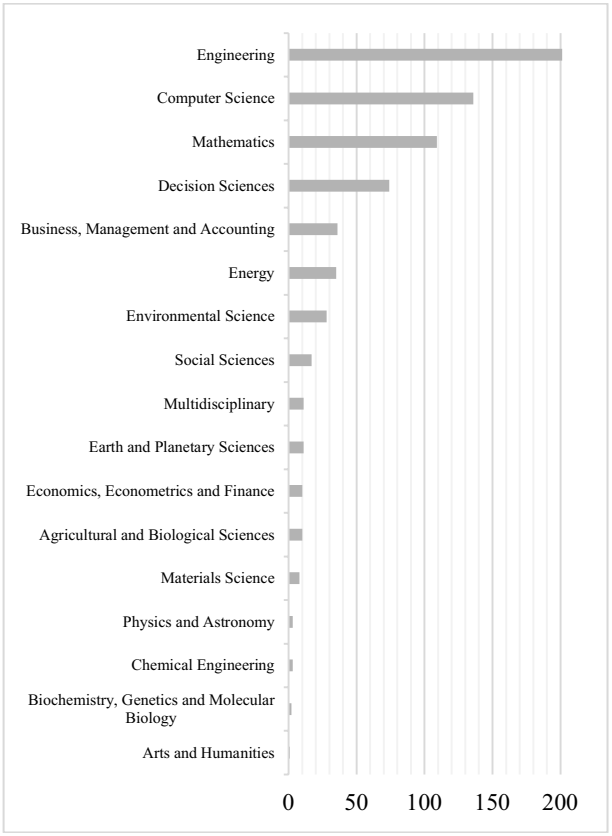

Figure 16. FMODM studies based on areas.

T.F. Liang, (with 11 publications) from Hsiuping University of Science and Technology, J. Xu (with 10 publications) from Sichuan University, R.Tavakkoli-Moghaddam (with 7 publications) from Islamic Azad University, Huang (with 6 publications), E. Ozceylan (with 6 publications) from Gaziantep University and T. Paksoy (with 6 publications) from Selçuk University are the most productive researchers in this field. Different techniques have been utilized in order to deal with FMODM problems. The most common utilized methods are fuzzy multiobjective linear programming (FMOLP), fuzzy multiobjective goal programming (FMOGP) and heuristic fuzzy MODM methods.

3.1. *Fuzzy Multiobjective Linear Programming*

Zimmermann [218] first extended his fuzzy linear programming approach to an ordinary multiobjective linear problem. For each of the objective functions of this problem, the decision maker is assumed to have a fuzzy goal. FMOLP has been used in many areas with an increasing interest. According to SCOPUS database, FMOLP was used in the titles of 4 papers in 2010; 7 papers in 2011; 5 papers in 2012; 13 papers in 2013 and 10 papers in 2014. The journals most publishing FMOLP studies are Fuzzy Sets and Systems, Applied Mathematical Modelling, and Computers and Industrial Engineering. FMOLP has been used in various areas in the literature [219-221]. The subject areas that FMOLP is most utilized for are Computer Science, Mathematics, Engineering and Decision Sciences.

3.2. *Fuzzy Multiobjective Goal Programming*

Charnes and Cooper [222] introduced the goal programming. Since decision makers may need to specify their goals for the objective functions under uncertainty and it may be hard to provide an accurate value for each goal, multi objective goal programming was extended to fuzzy case by Yaghoobi and Tamiz [223] , and Hannan [224].

According to SCOPUS database, FMOGP was used in the titles of 1 paper in 2010; 3 papers in 2011; 1 paper in 2012; 4 papers in 2013 and 5 papers in 2014. The journals most publishing FMOGP studies are Applied Mathematical Modelling, Fuzzy Sets and Systems, International Journal of Advanced Manufacturing Technology, International Journal of Operational Research, and Opsearch. FMOGP has been used in various areas in the literature ([225] [226]; [227]). The subject areas that FMOGP is most utilized for are Computer Science, Mathematics, Decision Sciences and Engineering.

3.3. *Fuzzy Heuristic MODM*

Most of the real-life optimization problems can be modeled with many conflicting objectives. This causes the concept of "optimal solution" to be abandoned and dealt with "efficient solution" and "efficient set". To solve these hard multiobjective problems, a number of fuzzy heuristic MODM techniques have been developed [228]. Some examples of fuzzy heuristic MODM are genetic algorithms [229], particle swarm optimization [230] and tabu search [231]. Tabu search and other heuristic methods have been relatively less used.

According to SCOPUS database, fuzzy heuristic MODM was used in the titles of 4 papers in 2010; 5 papers in 2011; 7 papers in 2012; 5 papers in 2013 and 6 papers in 2014. The journals most publishing fuzzy MODM genetic algorithms studies are Fuzzy Sets and Systems, Applied Soft Computing Journal, and Engineering Structures. The subject areas that fuzzy

MODM genetic algorithms are most utilized for are Engineering, Computer Science, Mathematics, and Energy.
From 2010 to 2014 the usage frequencies of fuzzy MODM particle swarm optimizations are 2, 2, 3, 3, and 3, respectively. The journals most publishing fuzzy MODM particle swarm optimizations studies are International Journal of Advanced Manufacturing Technology, Fuzzy Sets and Systems, Applied Soft Computing Journal, and Expert Systems with Applications. The subject areas that fuzzy MODM particle swarm is most utilized for are Engineering, Computer Science, Energy and Mathematics.

4. Trends and Directions

Table 16 presents the percentages of subject areas with respect to MADM methods. When we look at Table 16, the subject area engineering takes the first order in fuzzy ELECTRE, PROMETHEE, TOPSIS, AHP and ANP. The subject area computer science takes the first order in only fuzzy VIKOR and DEMATEL. We can conclude that the top five subject areas are almost the same: engineering, computer science, decision sciences, mathematics and business, management and accounting. We can also conclude that fuzzy MADM methods are rarely used in pharmacology, toxicology and pharmaceutics, psychology, health professions, neuroscience, immunology and microbiology, and nursing. From Table 16, it is also noticed that fuzzy ELECTRE is especially preferred for the solution of environmental science problems. We also examined the ratios that the number of publications using a fuzzy MCDM method for a certain subject area divided by the total number of the whole MCDM publications for the same subject area. Earth and planetary sciences and agricultural and biological sciences almost only prefer fuzzy AHP and fuzzy TOPSIS methods. Fuzzy VIKOR method is mostly used for economics, econometrics and finance areas.
The top five subject areas for fuzzy MODM methods are engineering with 29%, computer science with 19%, decision sciences with 16% , mathematics and business with 11%, and management and accounting with 5%. This ranking order is the same as fuzzy MADM methods. Fuzzy MODM is preferred as the second solution tool after fuzzy AHP for the energy subject area.
It is also seen that there is an exponential increase in the usage of fuzzy MCDM methods for the considered subject areas. This trend is expected to continue in the future years. It is also expected that fuzzy AHP and fuzzy TOPSIS methods will continue to be the most used methods. Fuzzy MODM methods will be frequently preferred for the solution of energy and economics, econometrics and finance problems.

Table 16. Percentages of subject areas with respect to MADM methods

Area	ELEC	PROM.	VIKOR	TOPSIS	AHP	ANP	DEM.
Eng.	0.21	0.21	0.23	0.28	0.29	0.28	0.21
Comp.	0.20	0.19	0.26	0.25	0.18	0.25	0.31
Math.	0.15	0.12	0.15	0.12	0.08	0.09	0.09
Dec.	0.14	0.14	0.07	0.07	0.06	0.10	0.07
Bus.	0.07	0.10	0.08	0.07	0.06	0.09	0.06
Soc.	0.02	0.08	0.03	0.04	0.06	0.04	0.04
Env.	0.08	0.05	0.03	0.03	0.05	0.04	0.07
Econ.	0.01	0.01	0.01	0.02	0.05	0.01	0.01
Earth.	0.02	0.02	0.02	0.02	0.04	0.01	0.03
Agri.	0.01	0.02	0.02	0.01	0.03	0.01	0.03
Energ.	0.03	0.01	0.03	0.03	0.02	0.02	0.01
Mult.	0.01	0.00	0.05	0.02	0.01	0.02	0.02
Phys.	0.01	0.00	0.01	0.01	0.02	0.01	0.00
Medi.	0.01	0.01	0.01	0.00	0.01	0.00	0.00
Mate.	0.01	0.03	0.01	0.01	0.01	0.01	0.00
Bioch.	0.01	0.00	0.01	0.01	0.01	0.01	0.02
Ch.	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Arts.	0.01	0.01	0.00	0.00	0.00	0.01	0.00
Ch.En	0.01	0.02	0.00	0.00	0.00	0.00	0.00
Phar.	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Psyc.	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Health	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Neur.	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Immu.	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nurs.	0.00	0.00	0.00	0.00	0.00	0.00	0.00

5. Conclusions

Fuzzy extensions of MADM and MODM methods have been extensively handled in the literature. Fuzzy versions of all kinds of MCDM methods have been developed and successfully applied to many problems in case of vague and in complete data. This paper has classified the fuzzy MADM and MODM methods with respect to their areas (computer science, engineering, decision sciences, etc.) distributions over years, publication media, and citation ranks. The most used application areas of fuzzy MADM and MODM methods are computer science, engineering, mathematics, decision sciences, business and management, and environmental sciences. The journals most publishing the applications and theoretical developments of fuzzy MADM and fuzzy MODM are Expert Systems with Applications, Computer Integrated Manufacturing Systems, International Journal of Production Research, European Journal of Operational Research, Computers and Industrial Engineering, and Fuzzy Sets and Systems. The distributions of papers with respect to their publication years yield a strong skewed to left

charts. This indicates that there is an exponentially increasing trend to use the fuzzy MADM and MODM methods. It is strongly expected that this trend will continue in the future.

For further research, we suggest another type of classification of fuzzy MCDM methods. For instance, a literature review for AHP can be made with respect to the used methods, i.e. the papers using Laarhoven and Pedrycz's fuzzy AHP [126], the papers using Buckley's fuzzy AHP [127], and the papers using Chang's fuzzy AHP [128].

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