Fuzzy decision making: A bibliometric-based review

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Abstract. Fuzzy decision-making consists in making decisions under complex and uncertain environments where the information can be assessed with fuzzy sets and systems. The aim of this study is to review the main contributions in this field by using a bibliometric approach. For doing so, the article uses a wide range of bibliometric indicators including the citations and the h-index. Moreover, it also uses the VOS viewer software in order to map the main trends in this area. The work considers the leading journals, articles, authors and institutions. The results indicate that the USA was the traditional leader in this field with the most significant researcher. However, during the last years, this field is receiving more attention by Asian authors that are starting to lead the field. This discipline has a strong potential and the expectations for the future is that it will continue to grow.

Keywords: Bibliometrics; fuzzy decision-making; Web of Science; VOS viewer.

1. Introduction

The research conducted on issues related to Fuzzy-Logic has its origin in the work of Zadeh [1]. This line of research analysed the concept of fuzzy sets starting from the use of classical Boolean sets to a multi-valued logic. Initially, this new theory received a great deal of criticism generating scepticism in the scientific community. However, this theory was able to establish itself as a research field, being studied by thousands of scientists around the world in both theoretical and practical aspects [2].

Within the multiple theoretical and practical developments, fuzzy logic stands out as a field of study of decision-making. The studies on fuzzy decision-making stemmed from studies of the concepts of fuzzy sets [1], fuzzy environments [3], approximate reasoning [4–6] and applications of fuzzy sets in decision systems [7] being developed a large number of research around the world.

Its main argument states that many of the decisions in the real world take place in an environment, in which the consequences of possible actions are not accurately known. Decision-making is a multistage process that is influenced by human subjectivity. Therefore, a fuzzy decision can be seen as an intersection of objectives and constraints given within a multistage process, where human intelligence has the ability to manipulate fuzzy concepts and fuzzy answer instructions [3].

It is widely accepted among academics and practitioners to use probabilistic methods for the analysis of decision-making. However, the traditional quantitative methods do not measure the uncertainty in human behaviour in a decision-making process [4]. As a result from this reasoning, fuzzy methods are became an effective tool to model this inaccuracy. The vagueness stems from mental phenomena, in which reasoning is approximate, i.e., the mode of reasoning is not accurate nor very inaccurate [4]. According to Chan and Hwang [8], a rational decision-making
process should take into account human subjectivity rather than using subjective measures of probability. Based on this premise, a more realistic framework of human reasoning has been developed, in which possibility is different than probability, i.e., high precision is incompatible with high complexity [4].

Based on the latter, decision-making has moved from the concept of probability to the concept of possibility, highlighting important differences between them. This new concept has created a theoretical framework for analysing information in a probabilistic and analog manner, in which the most important aspect is the meaning of the information that is measured [9]. This attitude towards information analysis analogously and the uncertainty of human behaviour is what has led to the study of a new field of decision analysis -fuzzy decision-making [8].

Research on decision-making is focused on dealing with problems of multiple criteria decision-making (MCDM), which takes into account the subjectivity of the decision-maker to select, prioritize, and organize different actions and observe the feasibility of an alternative option according to available resources. Thus, fuzzy theory is incorporated into the MCDM for the treatment of problems in situations within subjective uncertainty, since the objectives and constraints can involve linguistic variables and fuzzy variables [10]. Hwang and Yoon [11] suggest that the problems of multiple criteria decision-making can be classified into multiple attributes decision-making (MADM) and multiple objective decision-making (MODM). MADM is associated with problems whose numbers of alternatives have been predetermined; the decision-maker thus selects, prioritizes and ranks a finite number of actions to be undertaken MODM is not associated with problems in which the alternatives have been predetermined. The main interest of the decision maker is to design the “most” feasible alternative in relation to the limited resources [8]. According to Carlsson y Fullér [12] these methods are grouped into three categories: The first category contains several paths to find a ranking: Degree of optimalizad, Hamming distance, comparison function, fuzzy media and fuzzy scattering, to the ideal ratio, scores of left and right, index centroid, area measurement and methods linguistic classification. The second category contains methods that assess the relative importance of multiple attributes: simple additive weighting fuzzy methods, analytic hierarchy process, sets/disjunct, fuzzy outranking method and max-min fuzzy methods. The third category is the fuzzy mathematical programming: flexible scheduling, programming probabilistic, possibilistic linear programming using fuzzy max, robust programming, possibilistic programming with preferences fuzzy relations, fuzzy possibilistic programming objects.

Xu [13] has proposed uncertain multiple attribute decisions-making (UMADM) in order to rank and prioritize the information based on weight. UMADM used aggregation operators such as WA operator [14], OWA operator [15] and HWA [16], which are extended to other methods. UMADM treats known or partially known information considering their attribute preference weight, intervals and linguistic value. These new methods are then applied to current business issues such as supply-chain management, investment decision-making, personnel appraisal, product redesign and service maintenance. Currently, the research field of fuzzy decision-making has branched in new areas such as computer science, engineering, science operations management, mathematics, economic affairs and automatic control systems, bringing together a large number of researchers from around the world studying theoretical and practical aspects. Therefore it becomes interesting to analyse from a quantitative point-of-view, as this field has been developing since its inception.

Bibliometrics is a science that is based on quantitative analysis of articles published in a specific area. Bibliometric analysis allows us to evaluate either the impact or influence, in quality or performance, of scientific publications through the use of a bibliometric indicators [17]. These indicators allow us to analyse publications, citations and information sources which include articles, journals, authors, institutions and countries within a specific line of investigation. However, this type of study has many limitations, including co-authorship and self-appointment. According to Merigó et al. (2015), depending on the particular research style followed by each author, these can have a different volumes of articles with co-authorship and self-citations. Therefore, we use mapping science in order to analyse the structure of this field of research [18]. Thus, VOS viewer (visualization of similarities) is used for the structural analysis of citations. This software allows us to display information related to co-authorship, bibliographic coupling and co-citations in bibliometric map. It is noteworthy, that at present, bibliometric studies are much easier to conduct due to the strong development of computers and Internet access.
In current literature, there is a bibliometric study that offers a general overview of fuzzy research [2]. Some authors have made compilations of methods and applications for fuzzy decision-making [8, 10–13, 19–24]. Other authors have developed bibliometric studies in the field of computational intelligence that highlights fuzzy systems [25, 26], the evolution of the applications made in fuzzy sets theory [27], the development of Atanassov intuitionistic fuzzy set [28], review on aggregation operator research [29], visualization and quantitative research on intuitionistic fuzzy studies [30] and the development and viewing of research of fuzzy sets in Spain [31]. However, there is no evidence that indicates that a specific item provides a basic overview of research in the field of fuzzy decision-making.

The main aim is to present an overall view of the research in the field of fuzzy decision-making, from the work presented by Bellman and Zadeh in 1970 [3], making use of bibliometric techniques. The main idea is to show the development of this field of research within the research field of fuzzy logic according to the information obtained from the Web of Science (WoS). The study focuses mainly on the analysis of the evolution and development of this field of research considering articles, journals, authors, institutions and influential countries. In this sense, we can highlight the work of Herrera-Viedma, Xu, Herrera, Kahraman, Chichana, Tzeng, Huang and Yager as influential authors in this field of research. Likewise, it is also worth mentioning the importance of Fuzzy Set and Systems, Expert Systems with Applications, European Journal of Operation Research and Information Sciences as the main journals of research in fuzzy decision-making. Finally, the University of Granada stands as the most influential institution and the Islamic Azad University as the most productive. However, it is important to note that the WoS database has some limitations, since important research in this field can be omitted; however, the use of this database is recognized in the scientific community as the most important and stores the best scientific papers.

This article is organized as follows: Section 2 describes the methodology used. In section 3, the 30 most influential journals in this field are presented. In section 4, the most cited articles are presented. In section 5 the most influential authors are presented. In section 6, the universities that perform research in this field are analysed. In Section 7, the main conclusions from the article are exposed.

2. Methodology

For the development of this study, we have taken into account the information from the WoS database, which belongs to Thompson Reuters. This database also includes many other databases. In this study we consider the core science WoS collection. This database includes research of almost all sciences and contains information on more than 15,000 journals and 50,000,000 articles classified in about 251 categories and 151 areas of research [2]. To carry out the research process, we have used the keywords fuzzy and decision-making in the topic section. Thus, all items that are associated with research in decision-making in relation to fuzzy-research are generated. One of the limitations of using these words is that researches that is not directly related to fuzzy-research, but is related to decision-making appear. However, when analysing the information obtained in this field, it is easy to omit items as the fuzzy boundaries between research and related areas are not clear [2]. Thus, among the most relevant articles using the fuzzy words and decision-making and are not related to fuzzy investigations they are omitted to avoid imbalances.

In September 2015, there were 14,525 published pieces of work in WoS related to fuzzy decision-making. These matches include different types of research, such as journal articles, proceedings, book reviews, reviews, notes, comments, corrections and editorial material. For this study, we have included articles, reviews, letters and notes. After this filter, we reached a total of 9,173 selected work. Similarly, we have applied two filters which exclude papers published in 2015 and 2016, and have also omitted sub-areas, such as, multidisciplinary psychology, psychology, biology, forestry, applied psychology, political science, health. In the first filter, this time-period is not considered, since these periods are ongoing publications and our interest is to present the entries submitted during the last period updated by the WoS. Following this first filter, the number of entries remaining was 8,398. In the second filter, these areas are filtered for entries that, although matched keywords, are unrelated to the field of research. In this filter, 263 items were excluded. Finally, the sample used in this study was 8,135 published papers, which include articles, reviews, letters and notes. These papers are comprised between the years 1970 and 2014. This period has seen a large increase in publications, which implies that it is a field of research that is of great interest among researchers and
universities involved in fuzzy research (Fig 1). This is evidenced in that the total of fuzzy research made during the same period, 11.7% have been made in fuzzy decision-making. This increase is in line with the development of fuzzy research exposed by [2].

The ratio of this field of research (the number of publications per year in fuzzy decision-making in a year X in the WoS and total fuzzy research publications in a year X in the WoS) has been varying. During the first 24 years, for every 20 articles (articles, reviews, letters and notes) published on fuzzy research, one of them was focused on subject of fuzzy decision-making, i.e., 5% of the publications have been focused on this issue. In the past 21 remaining years, for each 10 articles (articles, reviews, letters and notes) published on fuzzy research, some of them dealt with the subject of fuzzy decision-making, i.e., 10% of the publications have focused on this topic. Another important aspect is that since breaking the barrier of a thousand fuzzy research publications per year in 1994, the percentage accumulated in fuzzy-research publications has increased 213%, where we can highlight the fuzzy decision-making line of investigation with an increase of 373%. Recently, in 2014, articles published in fuzzy decision-making have exceeded the 1000-publication barrier. These results emphasize the importance of this field of research within the fuzzy research.

One way to emphasize the importance of published articles is by the number of citations that published papers have in their field. Within the research in fuzzy decision-making, the most cited paper Chen [32] has 765 citations compared to the work of Zadeh [1] with more than 15,000 citations. Note that this work is the most cited in fuzzy research and lies within the 50 most cited articles of all time and all categories of the WoS [2]. Table 1 presents the general citation structure in fuzzy decision-making according to the data available in WoS. To evaluate the ratio of citations, limits have been established according to the number of items with higher citations to this limit. This classification shows that only 3 articles have received more than 500 citations, 5.25% of the items are equal to or more than 50 citations and 9.98% are between 25 and 49 citations. Within this analysis, it is also interesting to analyse the h-index [33]. This index is used to represent the importance of a group of articles. For example, an h-index of 20 means there are 20 elements having 20 or more appointments. For the whole of articles in this field, the h-index is 129.

Likewise, from the proposal of this index, several authors have studied its main characteristics, advantages and disadvantages proposing new indexes based on this [34]. The h-index can be applied to both articles, journals, authors, countries and universities. This allows us to make a holistic analysis of a certain field of research, taking into account several different items. The analysis of each item shows the
group of articles, journals, authors, countries and universities of more important in this field of research. Furthermore, in the case of journals, it also has taken into account the impact factor, which indicates their influence on the dissemination of the research topic.

On the other hand, science mapping is employed in order to build bibliometrical maps. This science can be described as a specific science, where scientific domains or fields of research are structured conceptually, intellectually and socially [18]. Thus, the VOS viewer software is used in order to analyse the structure of citations by authors, journals and universities. This software allows us to display information related to co-authorship, bibliographic coupling and co-citations in bibliometric map. This software has been implemented in more than 100 works of bibliometric analysis in both the social sciences and the sciences [35]. Of the aforementioned works, we can mention the one of [25], which makes bibliometric mapping a field of computational intelligence where one of their areas of investigation are fuzzy systems.

3. The 30 most influential journals in the field of fuzzy decision-making research

Fuzzy research works are published in a large number of journals. Some of these journals are very specific on the issue but others are more interdisciplinary. Below, in Table 2, the classifications of the 30 most influential journals are shown together with published works related to fuzzy decision-making.

Table 2. Leading journals in fuzzy decision-making research in WoS

| R | Journal | APFDM | H-FDM | TAP | TCFDM | ACFDM | PCFDM | %APFDM | IF | ≥500 | ≥200 | ≥100 | ≥50 |
|---|---------|-------|-------|-----|-------|-------|-------|--------|----|------|------|------|-----|
| 1 | ESA     | 607   | 51    | 12786 | 12619 | 6648  | 20.79 | 4.75%  | 2.240 | 3    | 6    | 36   | 1    |
| 2 | FSS     | 453   | 10594 | 18587 | 11328 | 41.03 | 4.28% | 1.986  | 15  | 20   | 67   | -    | -    |
| 3 | IS      | 282   | 49    | 9489  | 8070  | 5057  | 28.62 | 2.97%  | 4.038 | 5    | 11   | 31   | -    |
| 4 | JJIFS   | 211   | 13    | 1564  | 744   | 585   | 3.53  | 13.49% | 1.812 | -    | -    | -    | 1    |
| 5 | EJOR    | 201   | 51    | 20629 | 8804  | 6711  | 43.80 | 0.97%  | 2.358 | 8    | 16   | 28   | -    |
| 6 | ASC     | 195   | 27    | 2948  | 2835  | 2157  | 14.54 | 6.61%  | 2.810 | -    | 1    | 2    | 14   |
| 7 | KBS     | 153   | 29    | 2281  | 2613  | 1604  | 17.08 | 6.71%  | 2.947 | -    | 5    | 6    | -    |
| 8 | IEEEIFS | 128   | 34    | 1823  | 4448  | 3207  | 34.75 | 7.02%  | 8.746 | 2    | 10   | 12   | -    |
| 9 | JIFR    | 125   | 25    | 11468 | 2112  | 1657  | 16.90 | 1.09%  | 1.477 | -    | -    | 4    | 5    |
| 10 | IJIS    | 122   | 26    | 1578  | 2707  | 1847  | 22.19 | 7.73%  | 1.886 | -    | 1    | 5    | 7    |
| 11 | CIE     | 119   | 26    | 7365  | 1988  | 1622  | 16.71 | 1.62%  | 1.783 | -    | -    | -    | 9    |
| 12 | AMM     | 117   | 20    | 7300  | 1348  | 982   | 11.52 | 1.60%  | 2.251 | -    | -    | -    | 3    |
| 13 | JAKBS   | 113   | 23    | 1622  | 1349  | 14.35 | 10.69%| 1.783 | -    | -    | -    | -    | 3    |
| 14 | LIAMT   | 101   | 16    | 13204 | 982   | 797   | 9.72  | 0.70%  | 1.458 | -    | -    | -    | 3    |
| 15 | LNAI    | 92    | 9     | 41175 | 346   | 335   | 3.76  | 0.22%  | -    | -    | -    | -    | 1    |
| 16 | SC      | 87    | 15    | 1745  | 713   | 651   | 8.20  | 4.99%  | 1.271 | -    | -    | -    | 1    |
| 17 | LNCS    | 85    | 8     | 216058| 287   | 260   | 3.14  | 0.04%  | -    | -    | -    | -    | -    |
| 18 | CMA     | 79    | 24    | 13523 | 2117  | 1315  | 26.80 | 0.58%  | 1.697 | 1    | 3    | 9    | -    |
| 19 | ICIS    | 65    | 11    | 654   | 510   | 395   | 7.85  | 9.94%  | 0.574 | -    | -    | -    | 2    |
| 20 | IJPE    | 63    | 27    | 7677  | 2598  | 1992  | 41.24 | 0.82%  | 2.752 | -    | 2    | 4    | 11   |
| 21 | IJAR    | 62    | 27    | 1404  | 2126  | 1897  | 34.29 | 4.42%  | 2.451 | -    | 1    | 4    | 10   |
| 22 | MPE     | 62    | 4     | 7887  | 49    | 43    | 0.79  | 0.79%  | 0.762 | -    | -    | -    | -    |
| 23 | HITDM   | 61    | 14    | 552   | 628   | 463   | 10.30 | 11.05% | 1.406 | -    | -    | 1    | -    |
| 24 | JAM     | 52    | 3     | 2838  | 49    | 57    | 1.17  | 1.83%  | -    | -    | -    | -    | -    |
| 25 | FODM    | 49    | 14    | 210   | 885   | 702   | 18.06 | 23.33% | 2.163 | -    | 2    | 3    | -    |
| 26 | EAAI    | 48    | 14    | 2341  | 495   | 473   | 10.31 | 2.05%  | 2.207 | -    | -    | -    | 8    |
| 27 | DEDE    | 47    | 14    | 400   | 562   | 379   | 11.91 | 11.75% | 1.563 | -    | -    | -    | 1    |
| 28 | IJFS    | 46    | 9     | 382   | 335   | 263   | 7.28  | 12.04% | 1.095 | -    | -    | -    | -    |
| 29 | IEEEETSMCCPB | 46 | 23    | 2104  | 1881  | 1646  | 40.89 | 2.19%  | 6.220 | -    | 1    | 3    | 7    |
| 30 | IJGS    | 45    | 12    | 1454  | 961   | 899   | 21.36 | 3.09%  | 1.637 | 1    | -    | 4    | -    |

Source: Own elaboration based on WoS 2014. R: Ranking; H-FDM: H-FDM only with fuzzy decision-making; APFDM: Articles Published in Fuzzy Decision-Making; TAP: Total of articles published by journal; TCFDM: Total citations in Fuzzy Decision-Making; ACFDM: Articles in which it is cited in Fuzzy Decision-Making; PCFDM: Average of cites by article in Fuzzy Decision-Making; IF: Impact Factor; ≥500, ≥200, ≥100 and ≥50: articles with more of 500, 200, 100 and 50 citations. FSS: Fuzzy Sets and Systems; EJOR: European Journal of Operational Research; ESA: Expert Systems with Applications; IS: Information Sciences; JIFS: Journal of Intelligent & Fuzzy Systems; IEEEIFS: IEEE Transactions on Fuzzy Systems; ASC: Applied Soft Computing; KBS: Knowledge Based Systems; IJIS: International Journal of Intelligent Systems; IJPE: International Journal of...
Journals are ordered considering the number of articles published in the field of research and the h-index of each journal, which will be called H-FDM. In addition, it is noted that the journal Expert Systems with Applications (ESA) is the one with the highest amount of papers published in this field research with 607 articles and most influential journal is Fuzzy Sets and Systems (FSS) with an H-FDM of 69. It also shows that the percentage of articles published in fuzzy decision-making in relation to the total of its total publications is 4.28% for FFS and 4.75% for ESA. In addition, FSS has more articles with over 50 citations including 2 with more than 500 citations, 15 with more than 200 citations, 20 with more than 10 citations and 67 with more than 50 citations.

Other key journals in this field of research include Information Sciences (IS), Journal of Intelligent & Fuzzy Systems (JIFS), European Journal of Operation Research (JOR) and Applied Soft Computing. Among these journals, we can highlight JIFS, which has an H-FDM of 13 (which is very low compared to other journals in the Top 10) and with a percentage of articles published in fuzzy decision-making in relation to their total publications is of 13.49%, one of the highest in the Top-30 journals behind the FDM. However, this does not have an item that is influential, which is due to the fact that it is a new journal in relation to the others in the top-10.

A journal with great influence in this field is EJOR, which has an H-FDM of 51. However, the number of publications is lower, which is reflected in its 0.97% of publication share in this field, the lowest in the Top-10 journals. Its influence is reflected in having 8 items with more than 200 citations, 16 articles with more than 100 citations and 28 items with more than 50 citations landing it in second place with the highest amount of articles with over 50 citations behind FSS. Another journal with great influence is IS with an H-FDM of 49. It is noted that the percentage of articles published in fuzzy decision-making in relation to the total of its total publications is 2.97%, which is low compared to JIFS and other Top-30 journals. However, their influence is reflected by having 5 items with more than 200 citations, 11 items with more than 100 citations and 31 items with more than 50 citations locating it in third place with more premium items at 50 citations behind FSS and EJOR. However, it is one of the journals with the highest impact factor behind IEEEFS and OMEGA. Another important aspect to consider is the total number of citations in fuzzy decision-making (TCFDM) and articles that are cited in fuzzy decision-making (ACFDM). The FSS journal is notable for having a greater number of citations TCFDM with 18587 followed by ESA with 12619 citations. In a second group, we have an EJOR with 8804 citations, IS with 8070 citations and IEEEFS with 4448 citations.

The other journals have citations under 3,000. In this analysis, differences are obvious between the first and the second group, and even inside the first group. This is because the journal FSS is the first international journal created exclusively for fuzzy theories, which granted them the privilege of publishing the first studies that have become the foundations for this field. These differences are also evident in ACFDM. On the one hand, works on fuzzy decision-making published in FSS have been cited 11,328 times while his closest pursuers have cited 6,711 (EJOR), 6,648 (ESA) and 5,057 (IS). On the other hand, the average number of citations per article (PC) is a more balanced where we find 6 journals (FSS, EJOR, JIFS, IJPR, EEEETSMCPPB, IEEEETSMIPHA and OMEGA) with an average above 40.

In order to analyse how journals are structured in this field of research, we analysed citations and how they are connected to each other. The first analysis is focused on the bibliographic coupling (Bibcoup) with a threshold of at least 20 citations per article (see Fig 2). Also, co-citations from FDM journals (see Fig 3). In this case, we check 100 connections and a threshold of 500 citations.

In Fig 2, the existing connection by bibcoup is observed. Bibcoup occurs when two papers refer to a third joint-paper in their bibliographies. It is an indication that there is a likelihood that the two investigations focus on a related matter. This map shows three groups of journals that are relevant in this field of
In the first group, they highlight the ESA and EJOR journals, in the second FSS and IS and the third JIFS and ASC. Likewise, a group of more remote journals network is shown and are related to research on issues of environment and resource management. Thus, this map shows the connection between each of the journals and what there is influence of their investigation in this field of research.

Fig. 2. Mapping of journals bibliographic coupling with a threshold of 20 and considering the 100 most influential connections.

Fig. 3. Mapping of journal co-citations with a threshold of 500 citations and the 100 most representative connections.

Fig 3 shows in further detail the influence of the research. In this case, connections by co-citation can be observed. The co-citation shows us the possibility that a document B and C cited by a document A treat the same topic. For this study, we observe that the documents published in journals FSS, IS, EJOR and ESA are co-cited in the work related to research in fuzzy decision-making. Of these journals, FSS appears with the most connections followed by EJOR.

4. The 30 most influential papers in the field of fuzzy decision-making research.

An important issue to discuss in investigations in fuzzy decision-making are scientific publications. The most practical way to analyse is taking into account the times it is cited. The number of citations is an indicator that shows how influential and popular this article is within the development of the research field.

Table 3 exhibits the 30 most cited papers in fuzzy decision-making research. It is known that within the fuzzy research science the most cited article is Fuzzy Sets [1] with more of 15,000 citations [2]. However, there are other articles that appear in this ranking. It is also worth keeping in mind that these documents take into account classic research that has influenced investigation in fuzzy decision-making.

We can point out Intuitionistic fuzzy sets [36], Decision-making in a fuzzy environment [3], Multiple attribute decision-making [11], On ordered weighted averaging aggregation operators in multi-criteria decision-making [15], Families of OWA operators [37], Fuzzy sets [1], The concept of a linguistic variable and its application to approximate reasoning-I-II-III [4–6], Fuzzy sets as a basis for a theory of possibility [9], Results of empirical studies in fuzzy set theory [38], Fuzzy sets and decision analysis [39], Fuzzy sets, decision-making and expert systems [7], Fuzzy preference orderings in group decision-making [40], Group decision-making with a fuzzy linguistic majority [41], The analytic hierarchy process [42–44], Aggregation methods for decision-making [45], Intuitionistic fuzzy information aggregation [46], Linguistic information context [47], Intuitionistic fuzzy with probabilistic and OWA operator [48], New extension of OWAD operator [49] and Hybrid method for fuzzy decision making [50].

In research in fuzzy decision-making the most cited article is that of Chen [32] with 765 citations, which is published in FSS. Likewise, the article of Herrera and Herrera-Viedma [51] with 580 citations, also published in the journal FSS, is worth mentioning. It is emphasized that the authors Herrera F with 8 articles and Herrera-Viedma with 6 articles in the top 30
are the dominant within this list. Their work is mainly focused on the treatment of linguistic variables used in decision-making processes. Of the journals in which they publish, the FSS is dominant with 12 articles in the top-30 and 4 in the top 10 of this list. It should be taken into account that this list contains only articles published in scientific journals.

Table 3. 30 most cited papers in fuzzy decision-making research in WoS

| R | Title                                                                 | Authors                          | Journal | YP | TC  |
|---|----------------------------------------------------------------------|----------------------------------|---------|----|-----|
| 1 | Extensions of the TOPSIS For Group Decision-Making under Fuzzy Environment | Chen, CT                         | FSS     | 2000 | 765 |
| 2 | Linguistic Decision Analysis: Steps for Solving Decision Problems under Linguistic Information | Herrera, F; Herrera-Viedma, E | FSS     | 2000 | 580 |
| 3 | Decision-Making in A Fuzzy Environment                                | Bellman, RE; Zadeh, LA          | MS      | 1970 | 507 |
| 4 | Analytic Hierarchy Process: An Overview of Applications              | Vaidya, OS; Kumar, S            | EJOR    | 2006 | 461 |
| 5 | Condition Monitoring And Fault Diagnosis of Electrical Motors - A Review | Nandi, S; Toliyat, Ha; Li, XD   | IEEETEC | 2005 | 454 |
| 6 | Fuzzy Min Max Neural Networks .1. Classification                      | Simpson, PK                     | IEEETNN | 1992 | 423 |
| 7 | Fuzzy Support Vector Machines                                        | Lin, CF; Wang, SD               | IEEETNN | 2002 | 419 |
| 8 | Ranking Fuzzy Numbers With Integral Value                            | Liou, TS; Wang, MJ              | FSS     | 1992 | 407 |
| 9 | A Model of Consensus in Group Decision-making under Linguistic Assessments | Herrera, F; Herrera-Viedma, E; Verdegay, JI | FSS     | 1996 | 407 |
| 10 | A Fuzzy Approach for Supplier Evaluation and Selection in Supply Chain Management | Chen, CT; Lin, CT; Huang, SF | IJPE    | 2006 | 379 |
| 11 | Integrating Three Representation Models in Fuzzy Multipurpose Decision-making Based on Fuzzy Preference Relations | Chichana, F; Herrera, F; Herrera-Viedma, E | FSS     | 1998 | 378 |
| 12 | Some Geometric Aggregation Operators Based on Intuitionistic Fuzzy Sets | Xu, ZS; Yager, R.               | IJGS    | 2006 | 375 |
| 13 | Intuitionistic Fuzzy Aggregation Operators                           | Xu, ZS                          | IEEETFS | 2007 | 374 |
| 14 | Fuzzy Preference Orderings in Group Decision-Making                   | Tanino, T                       | FSS     | 1984 | 365 |
| 15 | An Overview of Operators for Aggregating Information                  | Xu, ZS; Da, QL                   | IJIS    | 2003 | 351 |
| 16 | A Model Based on Linguistic 2-Tuples for Dealing with Multigranular Hierarchical Linguistic Contexts In Multi-Expert Decision-Making | Herrera, F; Martinez, L        | IEEETSMC | 2001 | 350 |
| 17 | Is There a Need For Fuzzy Logic?                                     | Zadeh, LA                       | IS      | 2008 | 342 |
| 18 | Multicriteria Fuzzy Decision-Making Problems Based on Vague Set Theory | Hong, DH; Choi, CH              | FSS     | 2000 | 342 |
| 19 | Neuro-Fuzzy Rule Generation: Survey in Soft Computing Framework       | Mitra, S; Hayashi, Y            | IEEETNN | 2000 | 341 |
| 20 | Optimization Under Uncertainty: State-of-The-Art and Opportunities    | Sahinidis, NV                   | CCE     | 2004 | 340 |
| 21 | Group Decision-Making with a Fuzzy Linguistic Majority                | Kacprzyk, J                     | FSS     | 1986 | 329 |
| 22 | Direct Approach Processes in Group Decision-making using Linguistic OWA Operators | Herrera, F; Herrera-Viedma, E; Verdegay, JI | FSS     | 1996 | 327 |
| 23 | Application of Multi-Criteria Decision-making to Sustainable Energy Planning - A Review | Pohekar, SD; Ramachandran, M | RSER    | 2004 | 320 |
| 24 | Some Issues on Consistency of Fuzzy Preference Relations             | Herrera-Viedma, E; Herrera, F; Chichana, F; Luque, M | EJOR    | 2004 | 317 |
| 25 | Handling Multicriteria Fuzzy Decision-Making Problems Based on Vague Set-Theory | Chen, SM; Tan, JM               | FSS     | 1994 | 311 |
| 26 | A Fusion Approach for Managing Multi-Granularity Linguistic Term Sets in Decision-making | Herrera, F; Herrera-Viedma, E; Martinez, L | FSS     | 2000 | 300 |
| 27 | Advances in Diagnostic Techniques for Induction Machines              | Bellini, A; Filippetti, F; Tassoni, C; Capolino, GA | IEEETIE | 2008 | 299 |
| 28 | A New Approach for Ranking Fuzzy Numbers by Distance Method          | Cheng, CH                       | FSS     | 1998 | 298 |
| 29 | The Application of Fuzzy Integrals in Multicriteria Decision-making | Grabisch, M                     | EJOR    | 1996 | 296 |
| 30 | An Application of Soft Sets in A Decision-making Problem             | Maji, PK; Roy, AR               | CMA     | 2002 | 296 |

Source: Own elaboration based on WoS 2014. YP: Year Publication; TC: Total citation. Journal abbreviators are available in Table 2 except for MS: Management Science; IEEETEC: IEEE Transactions on Energy Conversion; IEEETNN: IEEE Transactions on Neural Networks; CCE: Computers & Chemical Engineering; RSER: Renewable and Sustainable Energy Reviews; IEEETIE: IEEE Transactions on Industrial Electronics; IEEETFS: IEEE Transactions on Fuzzy Systems.
Another important issue is to analyze the structure of the documents published in the fuzzy decision-making research. Fig 4 displays in further detail the influence of the existing work-connection by observing co-citations. The analysis has included classic research that does not appear in the initial search but are the cornerstone of fuzzy research. On this map the inference and the importance of the work of Zadeh [1] is evident. This work is located in the center where you can grasp the main research approaches in relation to fuzzy issues. It can be seen that four interest groups emerge. The first consists of the works of Zadeh [4–6], the second focal point on the work of Hwang and Yoon [11], the third focal point on the work of Atanassov [36] and the fourth central focus the work of Yager [15]. Thus, this structure illustrates that the development of research in fuzzy decision-making is focused on the treatment of linguistic variables, the degree of indecision and information aggregation to be organized. From these approaches, multiple investigations have been developed in which new algorithms that extend the original and applications in various fields are presented.

![Mapping of articles co-citations with a threshold of 500 citations and the 100 most representative connections.](image)

5. The 30 most influential authors in the field of fuzzy decision-making research

With the introduction of fuzzy theory in domains such as engineering and computer science, a great number of scientists have conducted research on this topic in different fields. In fuzzy research, we found authors who have a general influence in all fields (we speak of the pioneers) and others who have a specific impact on a specific topic, because the topic is developed in a particular direction.

In order to show which authors are the most influential in the fuzzy decision-making researches, the 30 most productive and influential authors in this field are presented in Table 4. This table is organized considering the number of publications by each author. The most prominent author regarding productivity is Xu ZS, who has published 137 articles, followed by Huang GH with 112 and Herrera-Viedma E with 82 published articles. In addition, three authors Xu ZS, Herrera-Viedma E and Herrera F stand out over others, because they have the highest indicators of influence showing their dominance in this area. The research papers of these authors focus on soft computing techniques for decision-making. For example, Xu ZS focuses on group decision-making, computing with words, aggregation operators, preference relations and intuitionistic fuzzy sets, Herrera-Viedma E focuses on the linguistic modeling, fuzzy logic, aggregation operators, consensus models, information retrieval and recommendations systems and Herrera F focuses on genetic algorithms applied in decision-making and data-mining. The most influential author is Herrera-Viedma E with an H-FDM of 44 followed by Xu ZS with an H-FDM of 39 and Herrera F with an H-FDM of 37. Similarly, it is observed that Herrera F with 8 articles and Herrera-Viedma E 6 articles. They have the largest number of publications in the Top-30.

Other aspects to be analyzed are the total citations in fuzzy decision-making (TCFDM), articles cited in fuzzy decision-making (ACFDM) and average citations per article (PCFDM) in fuzzy decision-making. In TCFDM, Herrera-Viedma E has 7384 citations, Herrera F has 6896 citations and ZS Xu 5626 citations. In ACFDM, Herrera F is cited in 2635 articles, Herrera-Viedma E is cited in 2560 articles, Yager RR is cited in 1863 articles and Xu ZS is cited in 1831 articles. This indicator shows us on how many articles they have been cited. In PCFDM, Herrera F has an average of 132.62 per article, Herrera-Viedma E has averaged 90.05 per article, Chiclana F has an average of 84.39 per article and Martinez L has an average of 62.47 per Article. Although Xu ZS is an influential author, his average citations of 41.07 is low relative to others authors in this list.
An interesting aspect is the source from which they are published, which is unrelated to the nationality of the author but rather to the geographical origin from which they come. In this sense, it should be noted that 54% of authors work in Asian countries, 34% in European countries, 10% in North and Central America and 2% in Oceania. From Asian countries, it is noteworthy that 74% are from the PRC, 14.8% are from Taiwan, 7.4% are from Iran and 3.7% are from Japan. Broadly, 30% of the authors of the Top-30 work in Chinese territory. Hence, it is obvious the dominance of Chinese authors in this field of investigation is due to its productivity. 4 countries in Europe, and 2 in North America are leaders this area research. Another important aspect to analyse is which of the authors within the Top-30 has more articles published in the 10 most influential journals. Note that the level of influence is given by the WoS.

Table 4. 30 most productive and influential authors in fuzzy decision-making research in WoS

| R | Name      | Country | TAPFDM | H-FDM | TCFDM | PCFDM | ACFDM | TOP 30 |
|---|-----------|---------|--------|-------|-------|-------|-------|--------|
| 1 | Xu ZS     | PRC     | 137    | 39    | 5626  | 41.07 | 1831  | 3      |
| 2 | Huang GH  | CAN     | 112    | 23    | 1626  | 14.52 | 851   | -      |
| 3 | Herrera F | ESP     | 82     | 44    | 7384  | 90.05 | 2560  | 6      |
| 4 | Kahraman C| TUR     | 70     | 26    | 2277  | 32.53 | 1541  | -      |
| 5 | Yager RR  | USA     | 62     | 22    | 2354  | 37.97 | 1863  | 1      |
| 6 | Tseng GH  | TWN     | 53     | 25    | 2039  | 38.47 | 1556  | -      |
| 7 | Li YP     | PRC     | 53     | 15    | 613   | 11.57 | 388   | -      |
| 8 | Herrera F | ESP     | 52     | 37    | 6896  | 132.62| 2635  | 8      |
| 9 | Merigo JM | ESP     | 50     | 21    | 1410  | 28.20 | 446   | -      |
| 10| Sakawa M  | JPN     | 49     | 14    | 636   | 12.98 | 477   | -      |
| 11| Li DP     | PRC     | 48     | 21    | 1431  | 29.81 | 785   | -      |
| 12| Wang J    | GBR     | 47     | 20    | 1650  | 27.30 | 630   | -      |
| 13| Martinez L| ESP     | 45     | 22    | 2811  | 62.47 | 1428  | 1      |
| 14| Wei GW    | PRC     | 44     | 17    | 1265  | 28.75 | 582   | -      |
| 15| Liu J     | GBR     | 44     | 14    | 577   | 13.11 | 453   | -      |
| 16| Chichana F| GBR     | 41     | 25    | 3460  | 84.39 | 1430  | 2      |
| 17| Chen TY   | TWN     | 41     | 14    | 625   | 15.24 | 427   | -      |
| 18| Pedrycz W | CAN     | 39     | 16    | 780   | 20.00 | 710   | -      |
| 19| Chen SM   | TWN     | 39     | 20    | 1614  | 41.38 | 1215  | 1      |
| 20| Zavadskas EK| LTU | 38     | 15    | 669   | 17.61 | 398   | -      |
| 21| Buyukozkan G| TUR | 37     | 18    | 1188  | 32.11 | 915   | 1      |
| 22| Ruan D    | TUR     | 36     | 16    | 1305  | 36.25 | 1019  | -      |
| 23| Liu PD    | PRC     | 36     | 14    | 609   | 16.92 | 347   | -      |
| 24| Tavana M  | USA     | 35     | 8     | 237   | 6.77  | 186   | -      |
| 25| Zhao XF   | PRC     | 34     | 11    | 431   | 12.68 | 277   | -      |
| 26| Zhang GQ  | PRC     | 34     | 14    | 605   | 17.79 | 499   | -      |
| 27| Chen XH   | PRC     | 33     | 9     | 330   | 9.43  | 244   | -      |
| 28| Sadiq R   | CAN     | 31     | 12    | 432   | 13.94 | 354   | -      |
| 29| Kacprzyk J| POL     | 31     | 16    | 1308  | 42.19 | 967   | 1      |
| 30| Xu JP     | PRC     | 30     | 7     | 167   | 23.86 | 147   | -      |

Source: Own elaboration based on WoS 2014. R: Ranking; : H index only with fuzzy decision-making; C: Country; TAPFDM: Total of Articles Published in Fuzzy Decision-Making; TCFDM: Total citation in Fuzzy Decision-Making; ACFDM: Articles in which is cited in Fuzzy Decision-Making; PCFDM: Average of cites by article in Fuzzy Decision-Making; TOP 30: Articles within Top 30. PRC: People's Republic of China; ESP: Spain; TUR: Turkey; TWN: Taiwan; CAN: Canada; GBR: United Kingdom of Great Britain & Northern Ireland; POL: Poland; LTU: Lithuania; JPN: Japan; USA: United States of America.

Table 5 shows the authors with more than 10 publications in the 10 most influential journals. These authors are sorted by the total publications in descending order. ZS is the most productive author with a total of 69 articles published in the 10 selected journals. Second place we find Herrera-Viedma E with a total of 50 published articles in the 10 selected journals. Herrera F appears third with a total of 39 articles in 7 of the 10 selected journals. Furthermore, it is noted that Sakawa is the author with the highest number of publications in FSS, Kahraman C in ESA, Herrera F in EJOR, Xu ZS in IS, KBS, IJIS and IJUFKBS, RR Yager in IEEETFS and IJAR and Chen TY in ASC.
In Fig 5, we observe a bibliometric map, where the connection existing between authors are established. These links allow us to observe the relationship between the work of the authors. In this map, four main nodes are highlighted. These nodes indicate that there are four central themes on which this field of research develop. Moreover, we can observe that each node has a referential author. In the first node, Xu ZS appears as the most influential, in the second we have Herrera-Viedma, in the third we observe Huang GH, and in the forth we have Kaharaman C and Tzeng GH. Within the network we can observe the links between nodes. This relation can be seen more clearly between node 1 and node 2. This indicates that there are common investigations that share methodologies and methods to be able to create new ones and develop new applications.
In Fig 6, we observe a bibliometric map where co-citation connections are established. It highlights 6 thematic nodes. In the main node we have Zadeh LA as the influential author on the five themes that addressed the research in fuzzy decision-making. This is evident because Zadeh LA is the father of fuzzy theory. On node 2 and 3 we located Yager RR and Xu ZS. These authors have focused on the development of aggregation operators for ordination of the information. In node 4 Herrera F and Herrera-Viedma E appear, who have focused on programming and linguistic reasoning. On node 5 we observe Saaty TL, who has focused on the analysis of the hierarchical process in order to analyse the relative importance of multiple attributes. On node 6, Zimmermann HJ appears, who has focused on fuzzy sets applied to decision-making and expert systems.

![Fig. 6. Mapping of author co-citations with a threshold of 300 citations and showing the 100 most representative connections.](image)

6. The 30 most influential universities in the field of fuzzy decision-making research

The development of research depends not only on researchers and their productivity. Behind all this work, we find institutions that welcome these researchers and support their work. The main institutions are universities that are directly interested in developing different fields of research. This research activity allows them to occupy a space in the academic world with more or less prestige. In the domain of investigation on fuzzy theory, many universities in the world have become interested in its development. Table 6 is displays the 30 most productive universities in this field of research, which takes into account indicators such as total publications, influence, origin and citations by universities. The most productive university is the Islamic Azad University with 221 papers published. Sharing second place in productivity are the University of Granada and the University of Tehran both with 144 published articles. In the fourth place is for the Istanbul Technical University with 128 articles and fifth National Chiao Tung University with 121 articles. The University of Granada is the most influential university with an H-FDM of 51. Second is National Chiao Tung University with an H-FDM of 34 and sharing third place in influence are National Cheng Kung University and Southeast University both with an H-FDM of 31. Clearly, the University of Granada, given their productivity and influence in this field of research is the most important and prominent among all the other universities. Its citation indicators evidence this. It has a TCFDM of 9646, the highest of all values and doubles the second most influential university.

Furthermore, its PCFDM is of 66,99 and possess ACFDM of 570. These indicators almost tripled and doubled the second most influential university. In addition, this university has 13 articles in the top-30, one article with more than 500 citations, 13 articles with more than 200 citations, 18 articles with more than 100 citations, 51 articles with more than 51 citations and 84 items with 1 and 50 citations. Knowing that the University of Granada has much higher indicators that of other universities in this field of research, other universities have entered smaller gap indicators that will be analysed.

The three universities distinguished for their TFD, we found the National Chiao Tung University with 3557, Southeast University with 3297 and University of Jaen with 3309. Of these three universities, the University of Jaen, which has a PCFDM of 48,66 and National stands Chiao Tung University with a PCFDM of 29,40. Likewise these universities have articles among the top-30, the University of Jaen with 4 articles, National Chiao Tung University with 2 articles and Southeast University with 1 article. Finally, it is noted that two of the most productive universities are Islamic Azad University and University of Tehran. However, these universities have lower indicators, which could be due to their recent support in this field of research.
The second and third nodes there is no a university that clearly surpass others. On the fourth node the most influential university is University of Granada. On the fifth node is a small group of universities which center University of Regina.

In Fig 8, we observe a bibliometric map where connections are established by co-citation. It highlights 2 different networks. In the first network, four nodes are observed while the second network presents a single node. This first network is noteworthy for having a center and two ends. At the bottom end there is a node in which Islamic Azad University is the center and its relation to the center of the network is specific. At the upper end there are two nodes. The
University of Granada influences the first. A sub-node follows this node. In the second node lies a Turkish university and in the sub-node, we observe one Polish and one Arab university. In the center of this network is a dense subnetwork, from which a large number of Asian universities are highlighted. The second network has no connection with the first, indicating that this group of universities are cited among them and focus on a specific topic.

7. Conclusions

We have presented a joint-vision of the research in fuzzy decision-making using bibliometric techniques. From a general point of view, we have taken a comprehensive approach to this field of research and its importance within fuzzy research in general. We have shown in general form as from the work of Zadeh [1] has developed this field until today.

It has highlighted the incorporation of fuzzy theory for the treatment of multiple criteria decision-making (MCDM) in order to treat problems in subjectively uncertain situations, which involve the limitations of language and fuzzy variables. We have set three classifications within MCDM, decision-making with multiple attributes (MADM), decision-making with multiple objective (MODM) and uncertain decision-making with multiple attributes (UMADM). The first one is associated with problems where the number of alternatives has been predetermined; the decision-maker thus selects, prioritizes and ranks a finite number of actions to be undertaken. The second is associated with the design of the "more" feasible alternative in relation to the limitation of resources. The third is associated to the first with exception that the ranking and prioritization of the information is according to their weight using aggregation operators.

With the incorporation of fuzzy theory in the study of decision-making, a new field of research began attracting the interest of a large number of researchers, universities and countries. This interest stimulated the production of a great deal of articles on different topics, which have been published by the most influential journals in the field of fuzzy research. For this reason, we made a bibliometric study in order to analyse the papers published in a quantitative manner. It has taken into account the h-index and the number of citations for each evaluated item. It has also made a structural analysis of the citations using this research field mapping. It has taken five areas of analysis by number of citations as the first item and its h-index. The topics chosen for analysis are articles, authors, magazines, universities and countries. Each area highlights its productivity and influence in this field of research.

Overall, this research field has been increasing its number of publications, which shows the interest placed on this area. At the country level, it is noted that USA remains the most influential country in the fuzzy research, including research in fuzzy decision-making. This result is expected since Lotfi Zadeh led
the origins of fuzzy research. In the case of fuzzy decision-making research, one of the most prominent authors is Ronald Yager and his contribution to the OWA aggregation operator. It also shows that the People's Republic of China is the second most influential and most productive country, due to the large number of researchers involved in the development of this field. With the large number of researchers who are located in China, Xu ZS stands out as the most productive and influential Chinese author highlighting their work with the aggregation operators and intuitionistic fuzzy information. Another country that stands out is Spain, which is in the Top-30 influence-wise and the Top-10 in productivity. The University of Granada (Spain) is the most influential in this field of research, far exceeding other universities in those indicators. Likewise, E. Herrera-Viedma at the University of Granada is the most influential researcher in fuzzy decision-making highlighting his work with the modeling language. Other universities distinguished for their influence are Istanbul Technical University, National Cheng Kung University, National Chiao Tung University, Southeast University, University of Jaen and the Islamic Azad University and University of Tehran for productivity. It also acknowledges Herrera, Kahraman, Chiclana and Tzeng for their influence and Huang for productivity.

Regarding the main outlets of this field, this analysis has focused on the ten most influential journals. Of these journals, Fuzzy Sets and Systems stands out as the most influential journal. This makes sense, since it is the first magazine created to publish papers on fuzzy theories and it is where the most influential papers are published in this field. Other prominent journals are Expert Systems with Applications, European Journal of Operational Research and Information Sciences, which are of fundamental importance in this field, since they have reached to publish works related to decision problems from different fuzzy approaches [52].

It is emphasized that this analysis is informative, because there are many limitations. First, we have considered articles, reviews, letters and notes, setting aside proceedings and books. Secondly, we have focused solely on the WoS Core Colletion, which may exclude important work in this field. However, the most representative works in this field are included in this database. Thirdly, it has been aimed at analysing the most productive and influential research. Finally, this study gives a general picture of this field of research and intends to showcase the importance and growth within fuzzy investigation.

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