Fuzzy decision making: A bibliometric-based review

Fabio Blanco-Mesa[a],*, José M. Merigó[b], Anna M. Gil-Lafuente[c]
[a]*Department of Business Administration, School of Business Administration, Antonio Nariño University, 7 Avenue 21-84, 150001, Tunja, Colombia*
[b]*Department of Management Control and Information Systems, School of Economics and Business, University of Chile, Av. Diagonal Paraguay 257, 8330015 Santiago, Chile*
[c]*Department of Business Administration, University of Barcelona, Av. Diagonal 690, 08034 Barcelona, Spain*
Emails: fabio.blanco@uan.edu.co (corresponding author); jmerigo@fen.uchile.cl; amgil@ub.edu

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 possibilistic 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 quantitive 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, Chiclana, 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 researches 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.

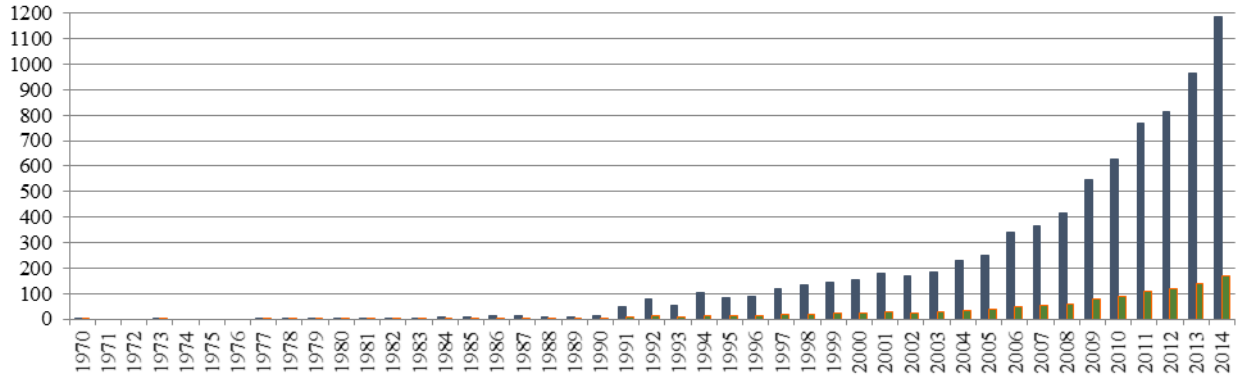

Fig. 1. Number of annual publications in WoS in fuzzy decision-making since 1970. The blue bars indicates the number of publications per year in WoS and the orange bars indicate the ratio (NPFDM/TPFR)x10000, where NPFDM is the number of publications in a year X in WoS and TPFR is the total number of publications in fuzzy research in a year X in WoS.

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.

Table 1. General citation structure in fuzzy decision-making research in WoS

Number of citations	Number of articles	% Articles
≥500	3	0,04%
≥250	36	0,44%
≥100	167	2,05%
≥50	427	5,25%
≥25	812	9,98%
≤25	6690	82,24%
Total articles	8135	

Source: Own elaboration based on WoS 2014

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
2	FSS	453	69	10594	18587	11328	41.03	4,28%	1.986	2	15	20	67
3	IS	282	49	9489	8070	5057	28.62	2,97%	4.038	-	5	11	31
4	JIFS	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	IEEETFS	128	34	1823	4448	3207	34.75	7,02%	8.746	-	2	10	12
9	IJPR	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	IJUFKBS	113	21	1057	1622	1389	14.35	10,69%	1.299	-	-	2	8
14	IJAMT	101	16	13204	982	797	9.72	0,76%	1.458	-	-	-	3
15	LNAI	92	8	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	IJCIS	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	7878	49	43	0,79	0,79%	0.762	-	-	-	-
23	IJITDM	61	14	552	628	463	10.30	11,05%	1.406	-	-	1	-
24	JAM	52	3	2838	61	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	-	-	-	-
27	TEDE	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	-	-	-	2
29	IEEETSMCCPB	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 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; ACFDMD: Articles in which is cited in Fuzzy Decision-Making; PCFDM: Average of cites by article in Fuzzy Decision-Making; %APFDM: Percentage of Articles published in Fuzzy Decision-Making (FDM/TAP); 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; IEEETFS: IEEE Transactions on Fuzzy Systems: ASC: Applied Soft Computing; KBS: Knowledge Based Systems; IJIS: International Journal of Intelligent Systems; IJPE: International Journal of

Production Economics; IJAR: International Journal of Approximate Reasoning; CIE: Computers & Industrial Engineering; CMA: Computer & Mathematics with Applications; IJPR: International Journal of Production Research; IJUFKBS: International Journal of Uncertainty Fuzziness and Knowledge-Based Systems; IEEETSMCCPB: IEEE Transactions on Systems Man and Cybernetics Part B-Cybernetics; AMM: Applied Mathematical Modelling; JEM: Journal of Environmental Management; IJAMT: International Journal of Advance Manufacturing Technology; OMEGA: OMEGA-International Journal of Management Science; SC: Soft Computing; FODM: Fuzzy Optimization and Decision-making; LNAI: Lecture Notes in Artificial Intelligence; LNCS: Lecture Notes in Computer Science; IJCIS: International Journal of Computational Intelligence Systems; MPE: Mathematical Problems in Engineering; IJITDM: International Journal of Information Technology & Decision-making; JAM: Journal of Applied Mathematics; EAAI: Engineering Applications of Artificial Intelligence; TEDE: Technological and Economic Development of Economy; IJFS: International Journal of Fuzzy Systems; IJGS: International Journal of General Systems.

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 most 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 (EJOR) 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 FODM. 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 IEEETFS 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 IEEETFS 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, IJPE, IEEETSMCCPB, IEEETSMSHPA 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

research. 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.

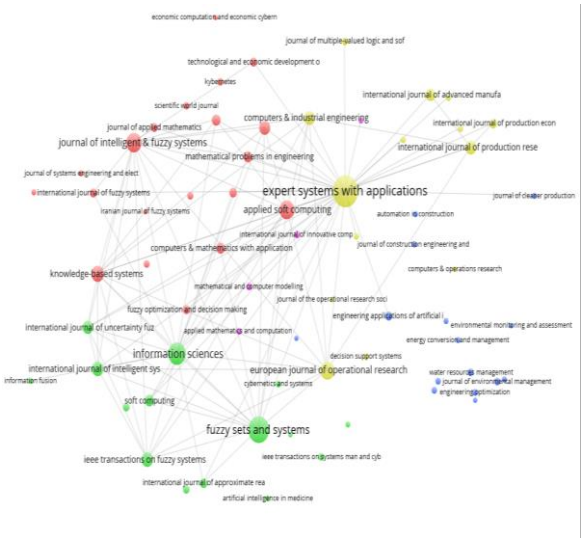

Fig. 2. Mapping of journals bibliographic coupling with a threshold of 20 and considering the 100 most influential connections.

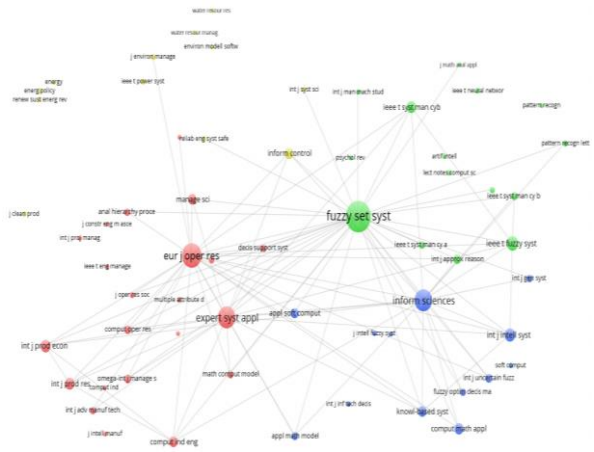

Fig. 3. Mapping of journal co-citations with a threshold of 500 citations and the 100 most representative connections.

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, MJJ	FSS	1992	407
9	A Model of Consensus in Group Decision-making under Linguistic Assessments	Herrera, F; Herrera-Viedma, E; Verdegay, Jl	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	Chiclana, 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 CPB	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, JL	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; Chiclana, 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.

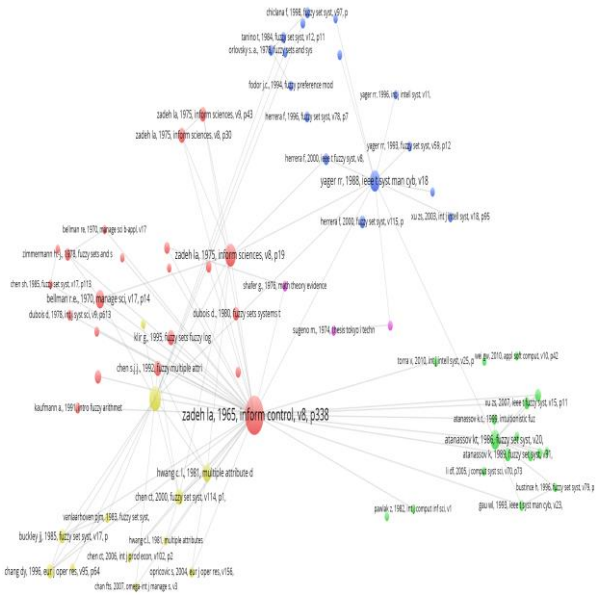

Fig. 4. Mapping of articles co-citations with a threshold of 500 citations and the 100 most representative connections.

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 TFDM, 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-Viedma E	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	Tzeng 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 DF	PRC	48	21	1431	29.81	785	-
12	Wang J	GBR	47	20	1650	27.50	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	Chiclana 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; ACFDMD: 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.

Table 5. Most productive authors within the 10 most influential journals in fuzzy decision-making research in WoS

R	Nombre	FSS	ESA	EJOR	IS	IEEETFS	KBS	ASC	IJAR	IJIS	IJUFKBS	TP
1	Xu ZS	3	2	4	10	7	10	4	3	15	11	69
2	Herrera-Viedma E	11	4	4	9	5	3	1	3	6	4	50
3	Herrera F	12	-	5	8	6	-	-	1	4	3	39
4	Yager RR	4	-	1	4	10	-	-	4	8	2	33
5	Chiclana F	5	2	3	3	3	5	2	1	5	2	31
6	Martinez L	3	2	1	7	6	3	-	-	2	7	31
7	Kahraman C	-	16	1	5	-	3	-	-	4	1	30
8	Sakawa M	16	3	4	3	-	-	-	-	-	-	26
9	Pedrycz W	8	2	3	3	3	1	1	3	1	-	25
10	Chen TY	1	5	2	8	-	1	5	-	-	-	22
11	Chen SM	4	12	-	3	2	-	-	-	-	-	21
12	Tzeng GH	3	5	3	3	-	3	2	-	-	2	21
13	Li DF	1	3	-	3	3	1	4	-	-	5	20
14	Wang YM	6	4	4	1	-	-	1	2	-	-	18
15	Merigo JM	-	8	1	4	-	-	-	-	2	1	16
16	Liu J	-	-	-	4	2	5	-	-	2	3	16
17	Cheng CH	4	3	4	-	-	-	4	-	-	1	16
18	Grabisch M	5	-	4	1	3	-	-	-	1	2	16
19	Ruan D	-	1	-	5	-	2	-	1	3	3	15
20	Kacprzyk J	5	-	2	1	1	-	-	-	4	2	15
21	Xia MM	1	-	-	2	1	4	1	1	4	-	14
22	Buyukozkan G	-	5	1	3	-	-	1	-	2	1	13
23	Wei GW	-	5	-	-	-	5	1	-	-	1	12
24	Tavana M	-	4	1	3	-	1	2	-	-	1	12
25	Yang JB	2	3	2	2	-	-	-	-	2	1	12
26	Wang J	1	4	1	3	-	1	1	1	-	-	12
27	Zhang GQ	1	4	1	1	2	2	-	-	-	1	12
28	Chen HY	1	4	-	1	-	2	2	-	1	1	12
29	Chen XH	-	1	-	4	-	1	2	-	2	1	11
30	Zhou LG	1	3	-	1	-	2	2	-	1	1	11

Source: Own elaboration based on WoS 2014. R: Ranking; FSS: Fuzzy Set and Systems; ESA: Expert Systems with Applications; EJOR: European Journal of Operation Research; IS: Information Sciences; IEEETFS: IEEE Transaction on Fuzzy Systems; KBS: Knowledge Based System; ASC: Applied Soft Computing; IJAR: International Journal of Approximate Reasoning; IJIS: International Journal of Intelligent Systems; IJUFKBS: International Journal of Uncertainty Fuzziness and Knowledge-Based Systems. TP: Total of Publications.

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 develops. 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.

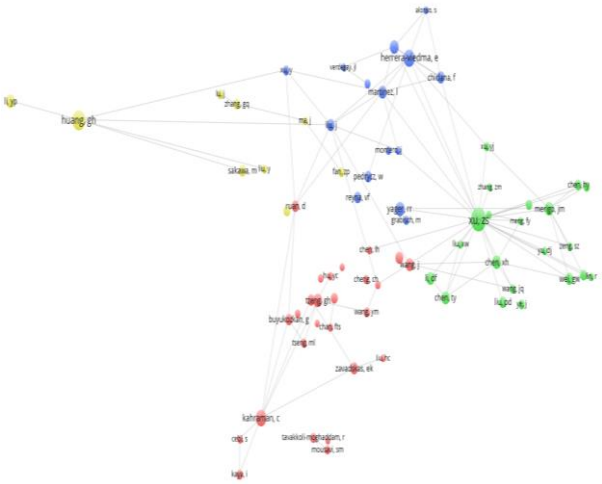

Fig. 5. Mapping of authors with at least 20 bibliographic couplings and the 100 most representative connections.

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.

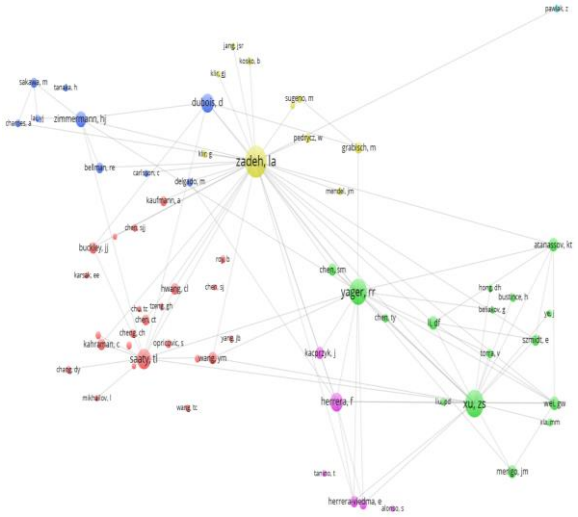

Fig. 6. Mapping of author co-citations with a threshold of 300 citations and showing the 100 most representative connections.

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 TFDM, we found the National Chiao Tung University with 3557, Southeast University with 3297 and Univesity 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.

Table 6. The 30 most productive universities in fuzzy decision-making research in WoS

R	Organizations	TPFDM	C	H-FDM	TCFDM	PCFDM	ACFDM	T30	≥500	≥200	≥100	≥50	<50
1	Islamic Azad Univ	221	IRI	19	1595	7.22	1577	-	-	-	1	2	169
2	Univ Granada	144	ESP	51	9646	66.99	3570	13	1	13	18	31	84
3	Univ Tehran	144	IRI	18	1147	7.97	973	-	-	-	-	1	116
4	Istanbul Tech Univ	128	TUR	29	2958	23.11	2062	1	-	3	3	12	87
5	Natl Chiao Tung Univ	121	TWN	34	3557	29.40	2969	2	-	2	4	15	92
6	Indian Inst Technol	110	IND	22	1878	17.07	2053	1	-	1	2	3	99
7	Natl Cheng Kung Univ	110	PRC	31	2398	21.80	1689	-	-	-	4	10	85
8	Southeast Univ	106	PRC	31	3297	31.10	1551	1	-	1	7	12	76
9	Univ Regina	99	CAN	22	1500	15.15	892	-	-	-	1	3	82
10	N China Elect Power Univ	88	PRC	18	1292	14.68	1080	1	-	1	1	3	67
11	Natl Taiwan Univ Sci T	87	TWN	24	1953	22.45	1244	-	-	-	2	12	65
12	Shanghai Jiao Tong Univ	87	PRC	22	1698	19.52	1552	-	-	-	5	3	63
13	City Univ Hong Kong	77	PRC	23	1965	24.87	1675	-	-	-	4	8	66
14	Pla Univ Sci Technol	75	PRC	20	1602	21.36	854	-	-	-	5	4	56
15	Iran Univ Sci Technol	74	IRI	13	601	8.12	585	-	-	-	-	1	62
16	CNRS	74	FRA	20	1411	19.07	1309	1	-	1	1	5	54
17	Hong Kong Polytech Univ	73	PRC	20	1563	21.41	1455	-	-	-	3	4	64
18	Galatasaray Univ	72	TUR	25	1846	25.64	1382	1	-	1	1	10	53
19	Yildiz Tech Univ	71	TUR	18	1058	14.90	884	-	-	-	-	5	53
20	Univ Manchester	69	GBR	26	2478	35.91	2067	1	-	2	6	6	47
21	Amirkabir Univ Technol	68	IRI	14	746	10.97	1645	-	-	-	1	2	53
22	Univ Jaen	68	ESP	28	3309	48.66	283	4	-	4	5	11	44
23	Iona Coll	68	USA	23	2550	37.50	1946	1	-	1	5	11	47
24	Sichuan Univ	68	PRC	10	395	5.81	651	-	-	-	-	-	53
25	Cent S Univ	63	PRC	15	713	10.97	481	-	-	-	1	3	44
26	Polish Acad Sci	61	POL	21	1914	31.38	1552	3	-	3	2	3	52
27	Fuzhou Univ	58	PRC	24	1721	29.67	1223	-	-	-	3	9	43
28	Tsinghua Univ	57	PRC	23	2364	41.47	1478	3	-	3	2	8	37
29	Chinese Acad Sci	55	PRC	14	678	12.33	590	-	-	-	-	4	45
30	Dalian Univ Technol	53	PRC	13	617	11.64	565	-	-	-	1	1	47

Source: Own elaboration based on WoS 2014. R: Ranking; TPFDM: Total of Publication in Fuzzy Decision-Making; C: Country; H-FDM: H index only with fuzzy decision-making; TCFDM: Total citation in Fuzzy Decision-Making; PCFDM: Average of cites by article in Fuzzy Decision-Making; ACFDMD: Articles in which is cited in Fuzzy Decision-Making; T30: Articles within Top 30; ≥500, ≥200, ≥100, ≥50 and <50: articles with more of 500, 200, 100 and 50 citations. ACFDMD: Articles in which is cited in Fuzzy Decision-Making; PCFDM: Average of cites by article in Fuzzy Decision-Making; %APFDM: Percentage of Articles published in Fuzzy Decision-Making (FDM/TAP); PRC: People's Republic of China; ESP: Spain; IRI: Iran; TUR: Turkey; TWN: Taiwan; IND: India; CAN: Canada; FRA: France; GBR: United Kingdom of Great Britain & Northern Ireland; POL: Poland; LTU: Lithuania; SIN: Singapore; JPN: Japan; BEL: Belgium; USA: United States of America.

So far we have analysed and highlighted the most productive and influential universities in this area. Now, we propose to analyse the structure of universities, to determine the connections between authors through their citations. In Fig 7, we observe a bibliometric map showing the connection existing between universities. These links allow us to observe the relationship between topics of the research in these universities. In this map highlights five main nodes. These nodes indicate that there are five core subjects on which universities are investigating. Furthermore, particular networks between universities are observed. On the first node from the left, the most influential university is Islamic Azad University. In 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.

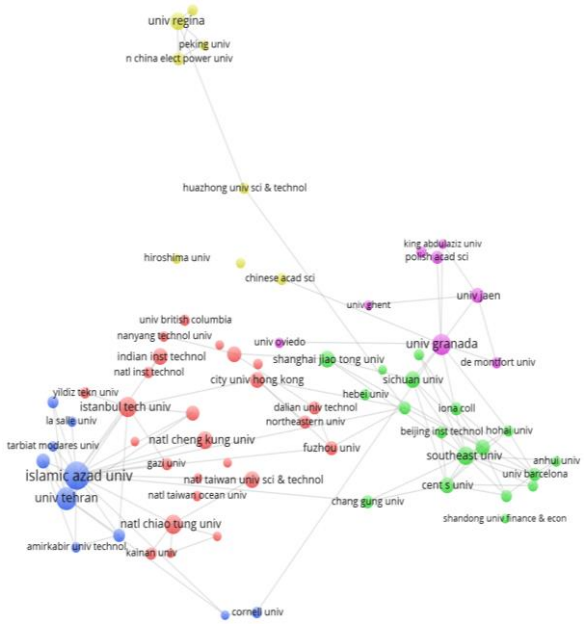

Fig. 7. Mapping of universities with more than 20 bibliographic couplings and the 100 most influential connections.

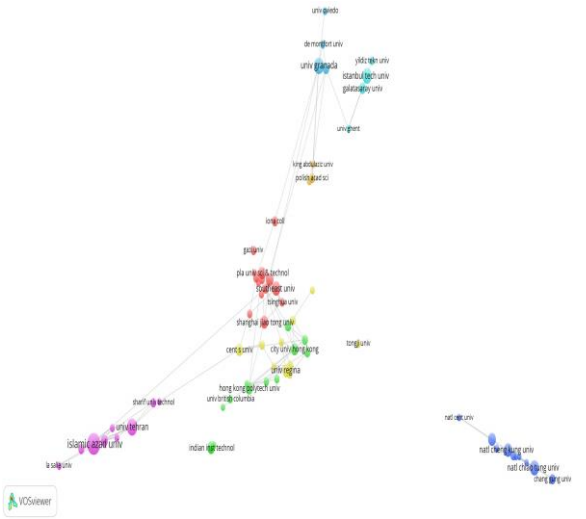

Fig. 8. Mapping of universities co-citations with a threshold of 500 and the 100 most representative connections.

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 universites 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 Istambul 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.

References

[1] L.A. Zadeh, Fuzzy sets, *Information and Control* **8** (1965), 338–353.

[2] J.M. Merigó, A.M. Gil-Lafuente and R.R. Yager, An overview of fuzzy research with bibliometric indicators, *Applied Soft Computing* **27** (2015), 420–433.

[3] R.E. Bellman and L.A. Zadeh, Decision-making in a fuzzy environment, *Management Science* **17** (1970), B–141–B–164.

[4] L.A. Zadeh, The concept of a linguistic variable and its application to approximate reasoning—I, *Informaiton Sciences* **8** (1975), 199–249.

[5] L.A. Zadeh, The concept of a linguistic variable and its application to approximate reasoning—II, *Information Sciences* **8** (1975), 301–357.

[6] L.A. Zadeh, The concept of a linguistic variable and its application to approximate reasoning—III, *Information Sciences* **9** (1975), 43–80.

[7] H.J. Zimmermann, *Fuzzy sets, decision making and expert systems*, Kluwer Academic Publishers, Netherlands, 1986.

[8] S.J. Chen and C.L. Hwang, *Fuzzy multiple attribute decision making: methods and applications*, Springer Berlin Heidelberg, Berlin, Heidelberg, 1992.

[9] L.A. Zadeh, Fuzzy sets as a basis for a theory of possibility, *Fuzzy Sets and Systems* **100** (1999), 9–34.

[10] G.H. Tzeng and J.J. Huang, *Multiple attribute decision making: Methods and applications*, Chapman and Hall/CRC, Boca Raton, 2011.

[11] C.L. Hwang and K. Yoon, *Multiple attribute decision making*, Springer Berlin Heidelberg, Berlin, Heidelberg, 1981.

[12] C. Carlsson and R. Fullér, Fuzzy multiple criteria decision making: Recent developments, *Fuzzy Sets and Systems* **78** (1996), 139–153.

[13] Z. Xu, *Uncertain multi-attribute decision making: Methods and applications*, Springer-Verlag Berlin Heidelberg, Berlin, Heidelberg, 2015.

[14] J.C. Harsanyi, Cardinal welfare, individualistic ethics, and interpersonal comparisons of utility, *Journal of Political Economy* **63** (1955), 309–321.

[15] R.R. Yager, On ordered weighted averaging aggregation operators in multicriteria decision-making, *IEEE Transactions on Systems, Man, and Cybernetics* **18** (1988), 183–190.

[16] Z. Xu, Hybrid weighted distance measures and their application to pattern recognition. In: Fyfe, C., Kim, D., Lee, S.-Y., and Yin, H. (eds.) *Intelligent Data Engineering and Automated Learning-IDEAL* 2008. pp. 17–23. Springer Berlin Heidelberg, Daejeon, 2008.

[17] H.F. Moed, New developments in the use of citation analysis in research evaluation, *Archivum Immunologiae et Therapiae Experimentalis* **57** (2009) 13–18.

[18] M.J. Cobo, A.G. López-Herrera, E. Herrera-Viedma and F. Herrera, Science mapping software tools: Review, analysis, and cooperative study among tools, *Journal of the American Society for Information Science and Technology* **62** (2011), 1382–1402.

[19] M. Sakawa, *Fuzzy sets and interactive multi-objective optimization*, Springer US, Boston, MA, 1993.

[20] J.C. Fodor and M.R. Roubens, *Fuzzy preference modelling and multicriteria decision support*, Kluwer Academic Publishers, Dordrecht, 1994.

[21] A. Kaufmann and J. Gil-Aluja, *Las matemáticas del azar y de la*

incertidumbre: elementos básicos para su aplicación en economía, Centro de Estudios Ramón Areces, Madrid, 1990.
[22] A. Kaufmann and J. Gil-Aluja, *Técnicas de gestión de empresa: previsiones, decisiones y estrategias*, Ediciones Pirámide, 1992.
[23] G.H. Tzeng and J.J. Huang, *Fuzzy multiple objective decision making*, CRC Press, Boca Raton, 2013.
[24] M. Sharma, Multi attribute decision making techniques, *International Journal of Research in Management, Science & Technology* **1** (2013), 49–51.
[25] N.J. van Eck and L. Waltman, Bibliometric mapping of the computational intelligence field, *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems* **15** (2007) 625–645.
[26] N.J. van Eck, J. Waltman, J.B. van Den and U. Kaymak, Field, visualizing the computational intelligence. *IEEE Computational Intelligence Magazine* **1** (2006), 6–10.
[27] M.J. Cobo, A.G. López-Herrera, E. Herrera-Viedma and F. Herrera, An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to the fuzzy sets theory field, *Journal of Informetrics* **5** (2011), 146–166.
[28] D. Yu and S. Shi, Researching the development of Atanassov intuitionistic fuzzy set: Using a citation network analysis, *Applied Soft Computing* **32** (2015), 189–198.
[29] D. Yu, A scientometrics review on aggregation operator research, *Scientometrics* **105** (2015) 115–133.
[30] D. Yu and H. Liao, Visualization and quantitative research on intuitionistic fuzzy studies, *Journal of Intelligent and Fuzzy Systems* **30** (2016), 3653–3663.
[31] A.G. López-Herrera, M.J. Cobos, E. Herrera-Viedma and F. Herrera, Visualization and evolution of the scientific structure of fuzzy sets research in Spain, *Information Research* **14** (2009), 1–23.
[32] C.T. Chen, Extensions of the TOPSIS for group decision-making under fuzzy environment, *Fuzzy Sets and Systems* **114** (2000) 1–9.
[33] J.E. Hirsch, An index to quantify an individual's scientific research output, *Proceedings of the National Academy of Sciences of the United States of America* **102** (2005), 16569–16572.
[34] S. Alonso, F.J. Cabrerizo, E. Herrera-Viedma and F. Herrera, h-Index: A review focused in its variants, computation and standardization for different scientific fields, *Journal of Informetrics* **3** (2009), 273–289.
[35] Leiden University: VOSviewer - Publications, http://www.vosviewer.com/Publications{#}Applied{_}publications, (2015).
[36] K.T. Atanassov, Intuitionistic fuzzy sets, *Fuzzy Sets and Systems* **20** (1986), 87–96.
[37] R.R. Yager, Families of OWA operators, *Fuzzy Sets and Systems* **59** (1993), 125–148.
[38] H.J. Zimmermann, *Results of empirical studies in fuzzy set theory*, Plenum Press, New York, 1978.
[39] H.J. Zimmermann, L.A. Zadeh and B. Gaines, *Fuzzy sets and decision analysis*, North-Holland, Amsterdam, 1984.
[40] T. Tanino, Fuzzy preference orderings in group decision making, *Fuzzy Sets and Systems* **12** (1984), 117–131.
[41] J. Kacprzyk, Group decision making with a fuzzy linguistic majority, *Fuzzy Sets and Systems* **18** (1986), 105–118.
[42] T.L. Saaty, *Analytical hierarchy process*, McGraw-Hill, New York, 1980.
[43] R.W. Saaty, The analytic hierarchy process: What it is and how it is used, *Mathematical Modelling* **9** (1987), 161–176.
[44] T.L. Saaty, How to make a decision: The analytic hierarchy process, *European Journal of Operational Research* **48** (1990) 9–26.
[45] J. Wu, R. Xiong and F. Chiclana, Uninorm trust propagation and aggregation methods for group decision making in social network with four tuple information, *Knowledge-Based Systems* **96** (2016), 29–39.
[46] D. Yu, Intuitionistic fuzzy information aggregation under confidence levels, *Applied Soft Computing* **19** (2014), 147–160.
[47] J. Wu, F. Chiclana and E. Herrera-Viedma, Trust based consensus model for social network in an incomplete linguistic information context, *Applied Soft Computing* 35 (2015), 827–839.
[48] S. Zeng, W. Su and C. Zhang, Intuitionistic fuzzy generalized probabilistic ordered weighted averaging operator and its application to group decision making, *Technological and Economic Development of Economy* **22** (2016) 177–193.
[49] S. Zeng, An extension of OWAD operator and its application to uncertain multiple-attribute group decision-making, *Cybernetics and Systems: An International Journal* **47** (2016) 363–375.
[50] S. Zeng, J. Chen and X. Li, A hybrid method for pythagorean fuzzy multiple-criteria decision making, *International Journal of Information Technology and Decision Making* **15** (2016) 403–422.
[51] F. Herrera and E. Herrera-Viedma, Linguistic decision analysis: Steps for solving decision problems under linguistic information, *Fuzzy Sets and Systems* **115** (2000) 67–82.
[52] D. Yu, D.F. Li, J.M. Merigó and L. Fang, Mapping development of linguistic decision making studies, *Journal of Intelligent & Fuzzy Systems* **30** (2016) 2727–2736.