

Visualization and evolution of the scientific structure of fuzzy sets research in Spain

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Abstract

Introduction. Presents the first bibliometric study on the evolution of the fuzzy sets theory field. It is specially focused on the research carried out by the Spanish community.

Method. The CoPalRed software, for network analysis, and the co-word analysis technique are used.

Analysis. Bibliometric maps showing the main associations among the main concepts in the field are provided for the periods 1965-1993, 1994-1998, 1999-2003 and 2004-2008.

Results. The bibliometric maps obtained provide insight into the structure of the fuzzy sets theory research in the Spanish community, visualize the research subfields, and show the existing relationships between those subfields. Furthermore, we compare the Spanish community with other countries (the USA and Canada; the UK and Germany; and Japan and Peoples Republic of China).

Conclusions. As a result of the analysis, a complete study of the evolution of the Spanish fuzzy sets community and an analysis of its international importance are presented.

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Introduction

Fuzzy set theory, which was founded by [Zadeh \(1965\)](#), has emerged as a powerful way of representing quantitatively and manipulating the imprecision in problems. The theory has been studied extensively over the past forty years and satisfactorily applied to problems (for examples, see [Dubois and Prade 1985](#), [Kahraman et al. 2006](#), [Klir and Yuan 1995](#), [Zimmermann 2001](#) or [Zadeh 2008](#)).

In Spain, the first paper on fuzzy set theory was published by Trillas and Riera ([1978](#)). From 1978 to the present, more than 1,500 papers on the topic have been published by the Spanish fuzzy set research community, as shown by the ISI Web of Science. The Spanish fuzzy set community ranks seventh in the “top-ten” ranking of the most productive countries on fuzzy set theory research, and it is the second European country (according to data from ISI Web of Science).

According ISI Web of Science, from 1965 more than one hundred thousand papers on fuzzy set theory foundations and applications have been published in journals. In spite of this huge number of published papers there has been no bibliometric study on the field.

In this paper, the first bibliometric study is presented analysing the research carried out by the Spanish fuzzy set community. It is done by means of bibliometric maps, which show the associations between the main concepts studied by the Spanish community. The maps provide insight into the structure of the field, visualize the research subfields and indicate the existing relationships among these subfields. To generate these maps we use the software [CoPalRed](#) which is based on the longitudinal mapping defined by [Garfield \(1994\)](#) and the co-word analysis ([Callon et al. 1983](#), [Callon et al. 1991](#), [Coulter et al. 1998](#), [Whittaker 1989](#)), which is a useful and powerful tool for describing and showing up the internal structure of a scientific field ([Bailón-Moreno et al. 2005](#), [Bailón-Moreno et al. 2006](#), [Leydesdorff and Zhou 2008](#), [Zhang et al. 2008](#)).

The study reveals the main themes treated by the Spanish fuzzy set theory community from 1978 to 2008. It also allows comparison with those themes treated by other important international communities such as the USA, Canada, the United Kingdom, Germany, Japan, the Peoples Republic of China and Spain, which are collectively known as the G7 group. These seven countries were selected because they satisfy three conditions:

1. they must be in the top ten of the most productive countries (according to data in the ISI Web of Science);
2. just two countries for each geographical area (America, Europe and Asia) are considered; and
3. their first paper on the topic had to be published before 1980 (inclusive).

We complete our study by showing a quantitative analysis of the visibility of the Spanish fuzzy set community according to ISI's Web of Science, and showing a quantitative analysis on the importance of Spanish fuzzy research on the international fuzzy research according to ISI Web of Science. Doing those studies and comparisons, the impact of the Spanish fuzzy set theory community is also measured.

Methods

The Co-word analysis

Co-word analysis is a content analysis technique that is effective in mapping the strength of association between information items in textual data ([Callon et al. 1983](#), [Callon et al. 1991](#), [Coulter et al. 1998](#), [Whittaker 1989](#)). It is a powerful technique for discovering and describing the interactions between different fields in scientific research ([Callon et al. 1991](#), [Bailón-Moreno et al. 2006](#), [Leydesdorff and Zhou 2008](#), [Zhang et al. 2008](#)). Co-word analysis reduces a space of descriptors (or keywords) to a set of network graphs that effectively illustrate the strongest associations between descriptors ([Coulter et al. 1998](#)).

According to Krsul:

"this technique illustrates associations between keywords by constructing multiple networks that highlight associations between keywords, and where associations between networks are possible". ([Krsul 1998: 80](#))

The basic assumption in bibliometric mapping ([Börner et al. 2003](#)) is that each research field can be characterized by a list of the important keywords. Each publication in the field can in turn be characterized by a sub-list of these global keywords. Such sub-lists are like DNA fingerprints of these published articles.

[Börner et al. \(2003: 185\)](#) suggest that these 'fingerprints' can be used as a similarity measure: "The more keywords two documents have in common, the more similar the two publications are, and the more likely they come from the same research area or research specialty at a higher level".

[Garfield \(1994, 1\)](#) suggests that longitudinal mapping can be used to plot the evolution of a field, and can be used by 'analysts and domain' experts to forecast trends in the field. Novices might also discover the key research areas and their interconnection.

According to [Börner et al. \(2003: 188\)](#), the process of constructing a bibliometric map can be divided into the following six steps:

1. collection of raw data,
2. selection of the type of item to analyse,
3. extraction of relevant information from the raw data,
4. calculation of similarities between items based on the extracted information,
5. positioning of items in a low-dimensional space based on the similarities, and
6. visualization of the low-dimensional space.

We now discuss how we implement each of these steps.

The first step in the process of bibliometric mapping, is the collection of raw data. In this paper, the raw data consist of a corpus containing 16,344 original papers, about fuzzy set theory produced by the G7 group from 1965 to 2008. These original papers were extracted from ISI Web of Science with the query number 1 on 7th January 2009:

```
query 1: (TS=fuzz* or SO=("FUZZY SETS AND SYSTEMS" OR "IEEE TRANSACTIONS ON FUZZY SYSTEMS")) AND CU=(SCOTLAND OR JAPAN OR CANADA OR SPAIN OR ENGLAND OR "NORTH IRELAND" OR USA OR "PEOPLES R CHINA" OR WALES OR GERMANY) AND Document Type=(Article).
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Where *TS* field is a search based on the *Topic*, *SO* field is a search based on *Journal Title* (*Fuzzy Sets and Systems* and *IEEE Transactions on Fuzzy Systems* are the two most important scientific international journals on the topic) and *CU* field is a search based on the *Country*.

In Figure 1, the numbers of retrieved papers from ISI Web of Science from 1965 to 2008 is shown.

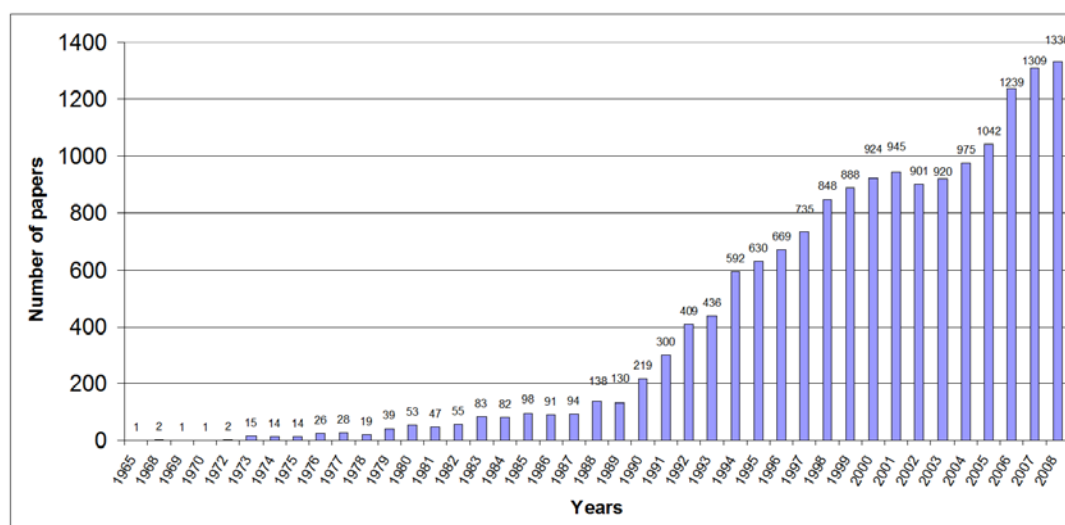


Figure 1: Retrieved papers from ISI Web of Science from 1965 to 2008 by query 1.

Two blocks of papers were collected, one for analysing the evolution of the fuzzy set theory field in all of the above mentioned countries taken together and another block to analyse the Spanish case. From these two blocks of papers, four subsets of papers are extracted, one for each studied sub-period: 1965-1993 (although the fuzzy sets based research in Spain started in 1978), 1994-1998, 1999-2003 and 2004-2008. In co-word analysis, in a longitudinal study, it is usual for the first sub-period to be the most long-lasting to get a representative number of published papers. For this reason, in this paper, the first studied sub-period includes twenty-nine years (from 1965 to 1993) and the other three sub-periods just five years. In this way, separate bibliometric maps can be constructed for each one of the four studied sub-periods. The number of papers in each block and sub-period is shown in Figure 2.

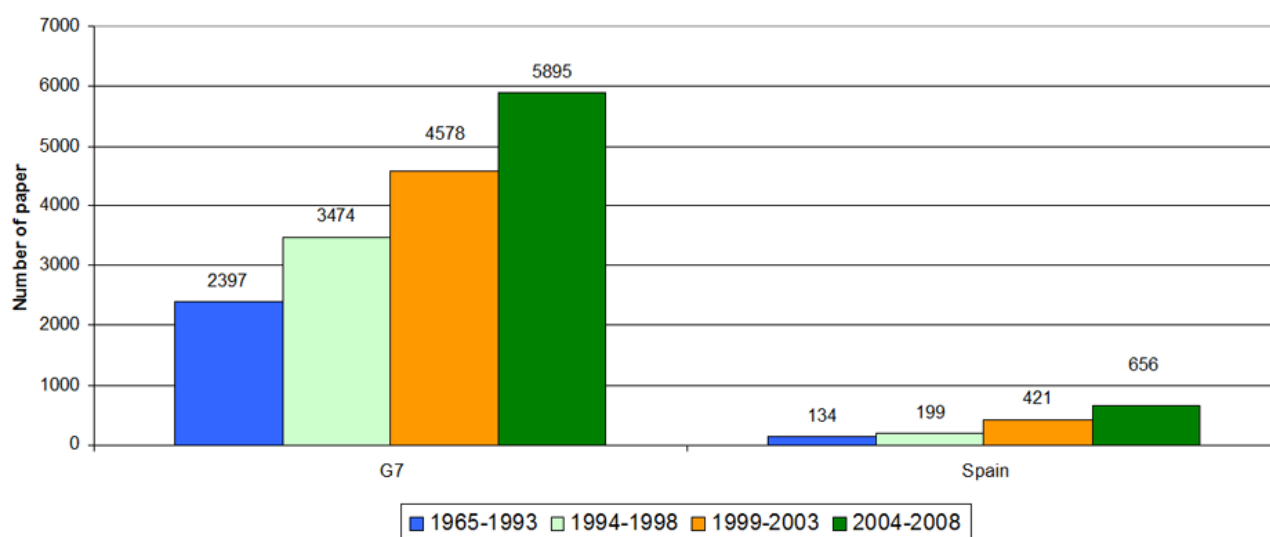


Figure 2: Number of papers in each block and sub-period.

The second step is the selection of the type of item to analyse. According to Börner *et al.* (2003), journals, papers, authors, and descriptive terms or words are most commonly selected as the type of item to analyse. Each type of item provides a different visualization of a field of science and results in a different analysis. In this paper, we chose to analyse descriptive words, i.e., keywords. A bibliometric map showing the associations between keywords in a scientific field is referred to as a keywords-based map in this paper.

The third step is the extraction of relevant information from the raw data collected in the first step (Börner *et al.* 2003). Here, the relevant information consists of the co-occurrence frequencies of keywords. The co-occurrence frequency of two keywords is extracted from the corpus of papers by counting the number of papers in which both keywords occur in the keywords section.

The fourth step is the calculation of similarities between items based on the information extracted in the third step (Börner *et al.* 2003). Here, similarities between items are calculated on the basis of frequencies of keywords co-occurrences. When two keywords frequently occur together, they are said to be linked, and the intensity of the link is indicated by the equivalency index (Michelet 1988, Callon *et al.* 1991), e_{ij} defined as:

$$e_{ij} = \frac{c_{ij}^2}{c_i c_j}$$

where c_{ij} is the number of documents in which two keywords i and j co-occur and c_i and c_j represent the number of documents in which each one appears. When the keywords appear together, the equivalency index equals unity; when they are never associated, it equals zero. Once the links are quantified, by an algorithm called *simple centres*, groupings or themes are produced, which consist of more strongly linked networks representing the centres of interest of the researchers.

As described by [Coulter et al. \(1998\)](#), the simple centres algorithm uses two passes through the data to produce the desired networks. The first pass (Pass-1) constructs the networks depicting the strongest associations and links added in this pass are called internal links. The second pass (Pass-2) adds to these networks links of weaker strengths that form associations between networks. The links added during the second pass are called external links.

[Coulter et al. \(1998\)](#) note that two keywords that appear infrequently in the corpus, but always appear together, will have higher strength values than keywords that appear many times in the corpus almost never together. Hence, possibly irrelevant or weak associations may dominate the network. A solution to this problem incorporated into the algorithm described in this section is to require that only the keyword pairs that exceed a minimum co-occurrence are considered potential links while building networks during the first pass of the algorithm. As each sub-period and block has different numbers of papers, different minimum co-occurrence values are used: 3, 4, 4 and 6 for the sub-periods 1978-1993, 1994-1998, 1999-2003 and 2004-2008, respectively for the G7 case; and 2 for all sub-periods for the Spanish case.

During the Pass-1, the link with the highest strength is selected first, its nodes becoming the starting nodes of the first Pass-1 network. Other links and their corresponding nodes are added to the graph using a breadth-first search on the strength of the links (i.e., the strongest link connecting a node that is not in any graph to the graph being constructed is added first), until there are no more links that exceed the co-occurrence threshold, or a maximum Pass-1 link limit is exceeded. The next network is generated in a similar manner starting with the link with the highest strength that is not in any existing graph.

Networks are interconnected by Pass-2 links. The *centrality* of a network measures the degree of interaction to other networks ([Callon et al. 1991](#)) and it can be defined as:

$$c = 10 * \sum e_{kh},$$

with k a keyword belonging to the theme and h a keyword belonging to other themes.

The *density* of a network measures the internal strength of the network ([Callon et al. 1991](#)) and it can be defined as:

$$d = 100 \frac{\sum e_{ij}}{w},$$

with i and j keywords belonging to the theme, and w being the number of keywords in the theme.

Isolated Networks are those that have low centrality values. *Principal Networks* are those that have high centrality and high density values, (for more detail see [Callon et al. 1991](#)).

The fifth step is the positioning of items in a low-dimensional space based on the similarities calculated in the fourth step ([Börner et al. 2003](#)). In this paper, the low-dimensional space is referred to as a *keywords based map* and only two-dimensional keywords based maps are considered. The two dimensions are centrality rank (cr) and density rank (dr), calculated as:

$$cr = \frac{rank_i^c}{N}; \quad dr = \frac{rank_i^d}{N}$$

where $rank_i^c$ is the position of the theme i in the theme list in ascending sort of centrality, and $rank_i^d$ is the position of the theme i in the theme list in ascending sort of density. N is the number of themes in the whole network. N is introduced to normalize in $[0,1]$ the centrality rank and density rank values.

The sixth step is the visualization of the low-dimensional space that results from the fifth step ([Börner et al. 2003](#)). In our study, we use CoPalRed computer program, which is briefly described in Subsection The [The CoPalRed software](#). CoPalRed visualizes the networks in a strategic diagram. A strategic diagram is a two-dimensional space in which themes are localized in strategic positions using the two measures, density rank (values in the ordinate axis) and centrality rank (values in the abscissa axis) (for more detail see [Callon et al. 1991](#)). The abscissa axis is associated to centrality, or the external cohesion index. It represents the most or least central position of a theme within the overall network. The ordinate axis is associated to density, or the index of internal cohesion. It represents the conceptual development of a theme.

Four areas of interest (or quadrants) can be defined in a strategic diagram (see Figure 3). Each quadrant has an associated theoretical meaning. The meaning of the four quadrants is:

- Quadrant 1 (upper-right): groups the *motor-themes* of the specialty, given that it presents strong centrality and high density.
- Quadrant 2 (upper-left): in this quadrant we find very specialised but peripheral themes.
- Quadrant 3 (lower-left): collects themes with low density and centrality and so mainly represents either emerging or disappearing themes.
- Quadrant 4 (lower-right): the transversal and the most general basic themes are localized in this quadrant, although with internal development not as high as those of quadrant 1.

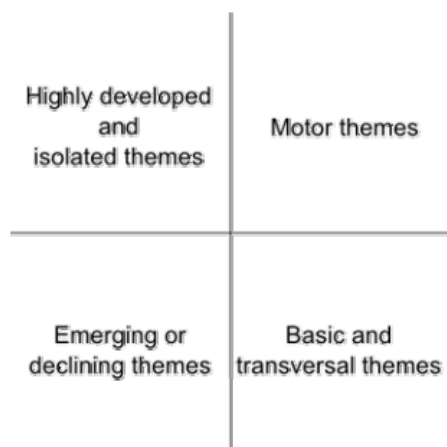


Figure 3: Quadrants in a strategic diagram.

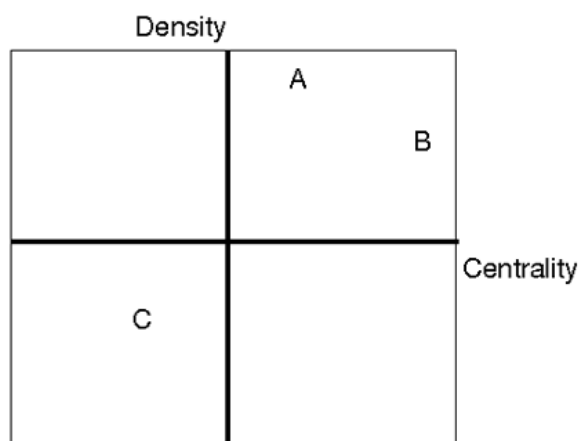


Figure 4: An example of strategic diagram.

CoPalRed visualizes a keywords-based map by displaying a sphere for each theme. This sphere indicates the location of the theme in the strategic diagram. The spheres can group and show representative information of the themes. In this paper, that information includes the name of the themes (identified by the most central keyword of the theme) and the number of associated papers. To do that, CoPalRed assumes a paper belongs to a theme when it presents at least 2 keywords of the theme.

As example, in the strategic diagram in Figure 4, the themes A, B and C are presented. The placement of theme B implies that this theme is quite related externally to concepts applicable to other themes that are conceptually closely related. In addition, the internal cohesion is also rather strong, and therefore we can consider B to be a *motor-theme* of the studied scientific field.

The CoPalRed software

In this paper the CoPalRed software (CoPalRed 2005) is used to generate the bibliometric maps.

CoPalRed has been successfully used to describe the field of physical chemistry of surfactants in (Bailón-Moreno *et al.* 2005, Bailón-Moreno *et al.* 2006).

CoPalRed performs three kind of analysis: structural analysis, strategic analysis and dynamic analysis.

- **Structural Analysis**, shows the analysis in the form of thematic networks in which words and their relationships are drawn. An example of thematic network is drawn in Figure 5. In it several keywords are interconnected, where the volume of the spheres is proportional to the number of documents corresponding to each keyword, the thickness of the link between two spheres i and j is proportional to the equivalence index e_{ij} .
- **Strategic Analysis**, places each thematic network in a relative position within the global thematic network, using two criteria: centrality (or intensity of its external relations) and density (according to their internal cohesion density). An example of strategic diagram is shown in Figure 4.
- **Dynamic Analysis**. CoPalRed analyses the transformations of the thematic networks over time. It identifies approaches, bifurcations, appearances and disappearances of themes.

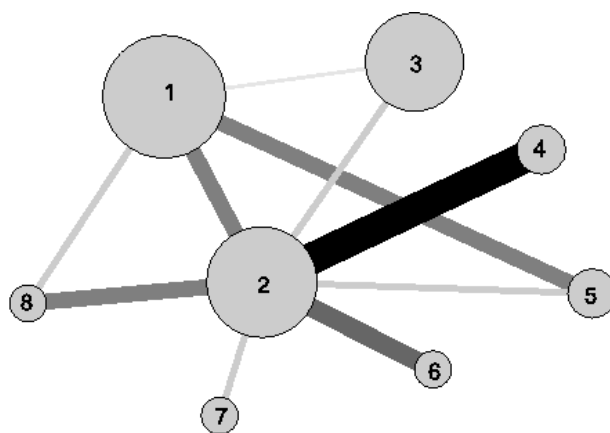


Figure 5: Example of thematic network.

Bibliometric study on fuzzy set theory research in Spain

This section analyses the evolution of the fuzzy set theory field over recent years. First, the evolution of the field in Spain is studied (including the

analysis of the fuzzy sets research carried out by the G7 countries and a comparison between both Spanish and International cases). Then, a snapshot of the visibility of the Spanish fuzzy community in the ISI Web of Science is presented. Finally, the importance of the Spanish community in the fuzzy set theory field is shown.

Evolution of Spanish fuzzy set theory research

To analyse the evolution of the fuzzy set theory field over the last years in Spain, strategic diagrams for the four studied sub-periods are shown in Figure 6. The volume of the spheres is proportional to the number of documents corresponding to each theme in each sub-period (a number is used to indicate the papers per theme). In the following the four sub-periods are described.

In the first studied sub-period (1978-1993), the longer one, in which there are barely enough papers (134) to get any important result, CoPalRed highlights three studied themes: *connectives* (five papers), *fuzzy-measure* (five papers) and *quantity* (four papers).

In the second sub-period (1994-1998), with 199 papers, CoPalRed shows nine themes, where *linguistic-preference-relations* (six papers) (the most central and dense theme), *linguistic-modelling* (six papers), *fuzzy-logic* (nine papers) and *fuzzy-control* (eight papers) were the four most studied themes.

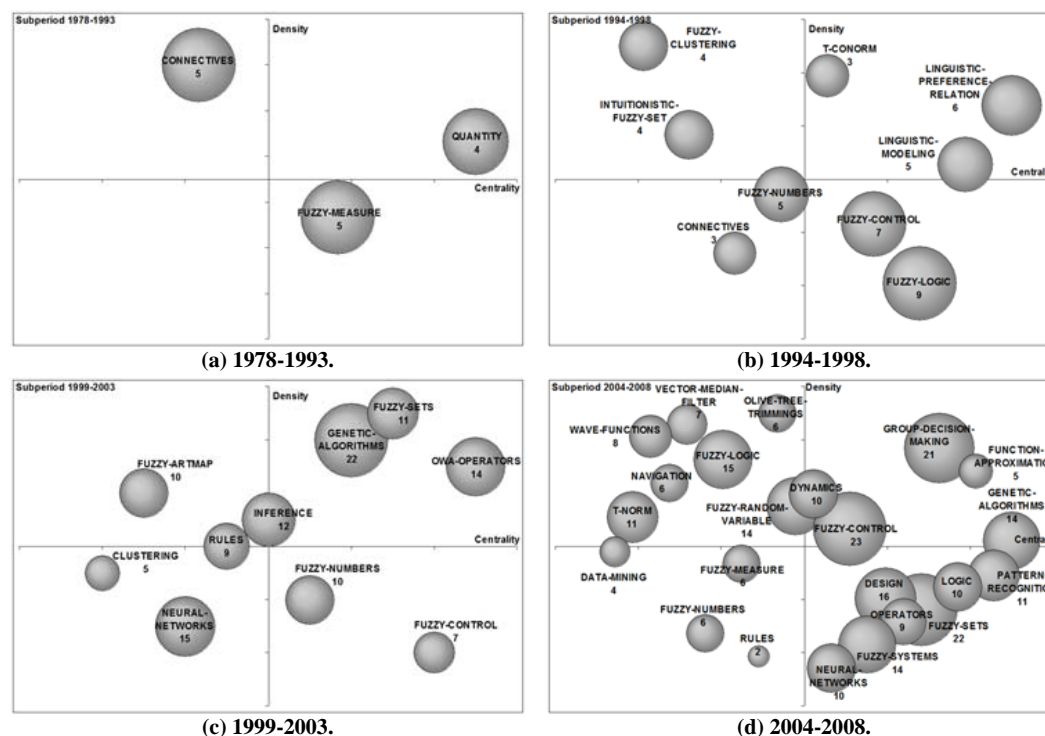


Figure 6: Strategic diagrams for each sub-period.

From 1999, a significant increment in published papers is observed, which allows us to carry out a more detail analysis. In the last decade (1999-2008) more themes and bigger ones are detected (see Figure 6, specially 6c and 6d).

From 1999-2003, the three most studied themes by the Spanish fuzzy sets research community were: *genetic-algorithms* (twenty-two papers), *neural-networks* (fifteen papers) and *OWA-operators* (fourteen papers). The themes *OWA-operators* and *genetic-algorithms* were the *motor-themes* of the sub-period (see Figure 6c).

From 2004 to 2008 the three most studied themes were the basic and transversal theme *fuzzy-sets* (with twenty-two papers), following by the most applied themes *fuzzy-control* (with twenty-three papers) and *group-decision-making* (twenty-one papers) (see Figure 6d).

From Figure 6 we can reach several conclusions in the evolution of the most long-lasting themes in the fuzzy sets research in the Spanish community:

- *Fuzzy-control* has increased its internal cohesion (its density) in the last five years (2004-2008). It indicates that the theme has been more studied and better developed (twenty-three vs. seven papers in the previous sub-period).
- *Genetic-algorithms* has consolidated in the upper-right quadrant. The number of published papers has decreased and the theme has become in a more central, basic and transversal one (see Figures 6c and 6d).
- The theme *group-decision-making* has showed up as a main theme (see Figure 7b). Previously, this was a minor topic related to other themes, such as *linguistic-preference-relations* in the studied sub-period 1994-1998 (see Figure 7a). The strategic position of group-decision-making in the upper-right quadrant indicates currently it is a *motor-theme* (see Figure 6d).
- The negative movement of *fuzzy-numbers*, from a position on the middle of the strategic diagram for sub-period 1994-1998 to the lower-left quadrant in 2004-2008, suggests that the theme is about to be discarded, as a research topic, by the Spanish community.
- Very specific themes have been also detected in the last sub-period; for example, *olive-tree-trimming*, which has been supported by six papers.

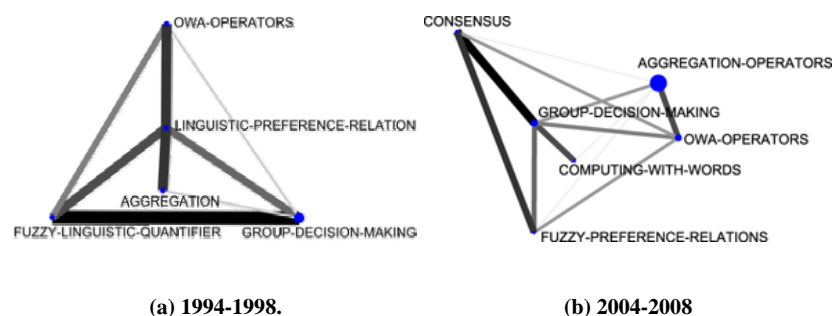


Figure 7: Group-decision-making thematic networks.

As summary, in [Table 1](#), the number of papers for each theme in each sub-period is shown. Columns 2 to 5 indicate the number of papers with the theme for each sub-period. Note: CoPalRed assumes a paper belongs to a theme when it presents at least two keywords of the theme.

Theme	1978-1993 (134 papers)	1994-1998 (199 papers)	1999-2003 (421 papers)	2004-2008 (656 papers)
Clustering			5	
Connectives	5	3		
Controller				7
Data-mining				4
Design				16
Dynamics				10
Function-approximation				5
Fuzzy-artmap			10	
Fuzzy-clustering		4		
Fuzzy-control		7	7	23
Fuzzy-measure	5	6		
Fuzzy-numbers		5	10	6
Fuzzy-logic		9		15
Fuzzy-random-variable				14
Fuzzy-sets			11	22
Fuzzy-systems				14
Genetics-algorithms			22	14
Group-decision-making				21
Inference			12	
Intuitionistic-fuzzy-sets		4		
Linguistic-modeling		5		
Linguistic-preference-relations		6		
Logic				10
Navigation				6
Networks				9
Neural-networks			15	10
Olive-tree-trimmings				6
Operators				9
OWA-operators			14	
Pattern-recognition				11
Quatity	4			
Rules			9	2
Systems		8		34
T-Conorm		3		
T-Norm				11
Vector-median-filter				7
Wave-functions				8

Table 1: Evolution of themes in number of papers published by Spanish authors.

To complete the description of the evolution of the fuzzy sets based research in Spain, in [Appendix A](#), Figures 13, 14, 15 and 16, show the complete relations among keywords and themes for each sub-period. In these networks, the volume of the spheres is proportional to the number of documents corresponding to each keyword, the thickness of the link between two spheres i and j is proportional to the equivalence index e_{ij} . Keywords belonging to a theme are labelled with the same number and each number represents a theme. Different numbers are used in each sub-period. Only the strongest relations are shown.

Evolution of international fuzzy set theory research

To analyse the recent evolution of the fuzzy set theory field in the above mentioned G7 countries, strategic diagrams for the four studied sub-periods (1965-1993, 1994-1998, 1999-2003 and 2004-2008) are shown in Figure 8. The volume of the spheres is proportional to the number of documents corresponding to each theme in each sub-period (a number is used to indicate the papers per theme). In the following the four sub-periods are described.

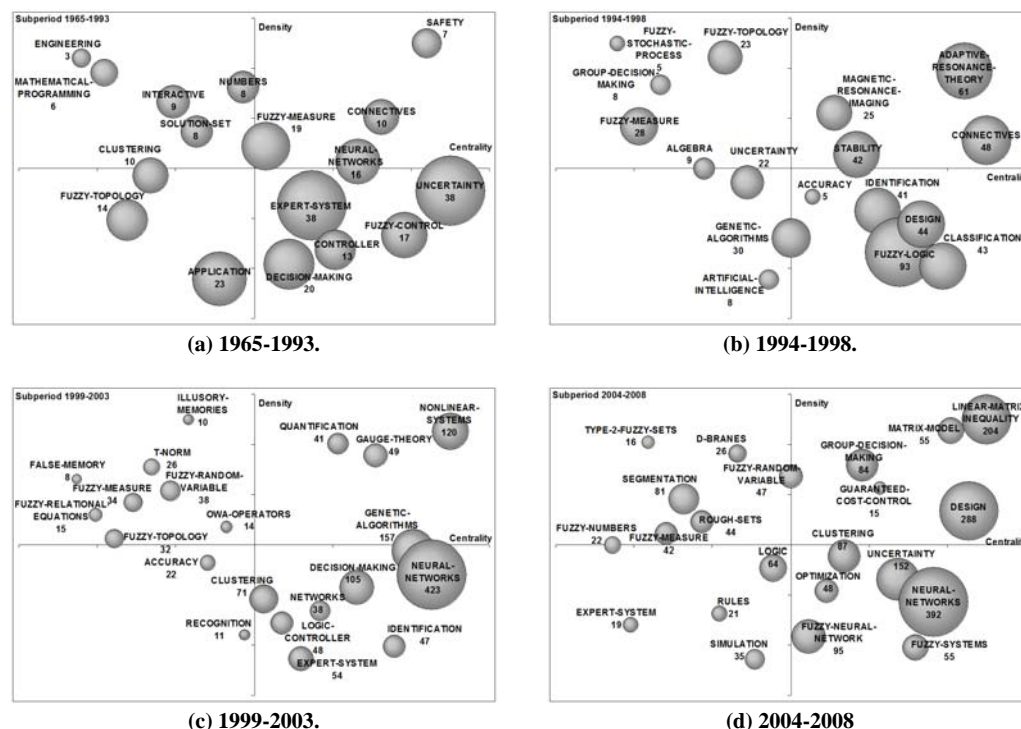


Figure 8: Strategic diagrams for each sub-period (G7 group).

In the first sub-period (1965-1993), the longer one, in which 2,397 papers were published, the most important themes in the international context (Considering the countries: USA, Canada, UK, Germany, Spain, Japan and Peoples Republic of China), in relative weight in terms of number of documents, were: *uncertainty* and *expert-systems* (both with thirty-eight papers), *applications* (twenty-three papers) and *decision-making* (with twenty papers) (see Figure 8a). Because of their strategic situation (lower-right quadrant), *uncertainty* and *expert-systems* and *decision-making* are considered as general basic themes, with high centrality, although with low internal development. In this first sub-period, the most central theme was *uncertainty*, the fuzzy set theory revolve around this concept.

In the second period (1994-1998), with 3,474 papers, *fuzzy-logic* (ninety-three papers), *adaptive-resonance-theory* (61 papers), *connectives* (48 papers), were the three most studied themes.

In the last decade, from 1999 to 2008, a significant increment in published papers is observed (see Figure 2). In these years (sub-periods 1999-2003 and 2004-2008) the number of interest topics of the international fuzzy community was augmented, and a set of different themes has been observed by CoPalRed (see Figure 8).

From 1999-2003, the most studied themes were: *neural-networks* (423 papers), *genetic-algorithms* (157 papers), *non-linear-systems* (120 papers), *decision-making* (105 papers) and *expert-systems* (54 papers). All of them were strategically localized in the right quadrants (with high centrality indexes) of the strategic diagram for this sub-period, i.e., they were quite related externally to concepts applicable to other themes that were conceptually closely related. In this sub-period, the most central and dense theme was *non-linear-systems*, and due to its strategic localization it was considered as the *motor-theme* of the sub-period.

From 2004 to 2008 the studied themes were those shown in the strategic diagram of Figure 8d. In this last sub-period, the principal themes, in number of papers, were *neural-networks* (392 papers), *design* (288 papers), *linear-matrix-inequality* (204 papers), *uncertainty* (152 papers), *fuzzy-neural-networks* (95 papers) and *group-decision-making* (84 papers). In this last sub-period, the theme *linear-matrix-inequality* was considered as the *motor-theme* of the sub-period.

From Figure 8 we can appreciate several conclusions in the evolution of the most long-lasting themes in the fuzzy sets based research in the G7 group:

- Basic and precursor themes as *uncertainty* have always been important research topics. In Figures 8a and 8d we can see as *uncertainty* has maintained its basic and traversal feature (lower-right quadrant).
- The themes *decision-making* and *group-decision-making* are ones of the most long-lasting applied themes.
- *Decision-making*, which was positioned in the lower-right quadrant, with high centrality and very low density (in the sub-period 1965-1993), increased its density and centrality in the lustrum 1999-2003. It can be seen in Figures 8a and 8c.
- The theme *group-decision-making*, which was in a very peripheral localization (upper-left quadrant) in 1994-1998 has become in a *motor-theme* in the last five years (2004-2008).
- The theme *genetic-algorithms* consolidated, in the decade 1994-2003, as an important theme in the fuzzy sets research (see Figures 8b and 8c). It increased values of both centrality and density to become one of the most central and studied themes (with 157 papers it was the second most studied theme in 1999-2003). In the last five years (sub-period 2004-2008), this theme has been absorbed by the theme *neural-networks* (as we can see in the thematic network in Figure 9).
- The negative movement (to the lower-left quadrant) of the theme *expert-systems* in the last ten years (1999-2008) is very surprising. *Expert-systems* was one of the most studied themes in the first sub-period (1965-1993). This decline can be seen in more detail in Figures 8a, 8c and 8d.
- It is very interesting to see as very recent theories and methods, such as *type-2-fuzzy-sets* (whose first papers date from the late 1990s) are still considered as very peripheral and specific topics by the international fuzzy sets research community (see Figure 8d).

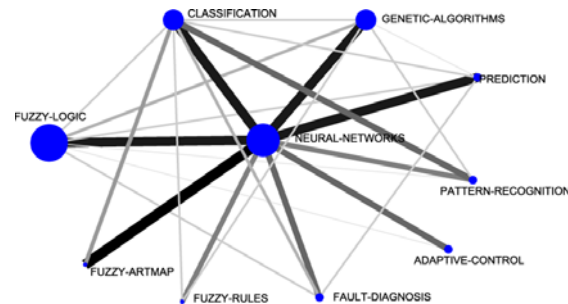


Figure 9: *Neural-Networks* thematic network (sub-period 2004-2008).

To complete the description of the evolution of fuzzy sets research in the G7 group, in [Appendix A](#), Figures 17, 18, 19 and 20, the whole relations among keywords and themes for each sub-period are shown. In these whole networks, the volume of the spheres is proportional to the number of documents corresponding to each keyword, the thickness of the link between two spheres i and j is proportional to the equivalence index e_{ij} . Keywords belonging to a theme are labelled with the same number and each number represents a theme. Different numbers are used in each sub-period. Only the strongest relations are shown.

Spanish vs international fuzzy set theory research

In this subsection, we show some conclusions about the fuzzy sets research carried out by the Spanish community compared with that of the seven studied countries (the G7 group).

From 1994-1998, whereas in the G7 group, the theme *connectives* (with forty-eight papers) was the most central theme (upper-right quadrant), in the Spanish research, *connectives* was situated in the lower-left quadrant (with just three papers). In the G7 group, the most studied theme was *fuzzy-logic* (with ninety-three papers), in the Spanish community just nine papers were published on this topic (see Figures 8b and 6b).

From 1999-2003, the theme *neural-networks* was supported by 423 papers in the G7 group, whereas in the Spanish community it received only fifteen papers. In addition, *neural-networks* in the G7 group, was better located (lower-right quadrant). Another important theme in this sub-period was *genetic-algorithms*, which was located in both cases in the upper-right quadrant. In both case, it was one of the most studied themes in the sub-period.

In the last five years (2004-2008), more similarities can be remarked upon. For example, the themes *fuzzy-random-variable*, *group-decision-making*, *neural-networks*, *fuzzy-systems* and *rules* were located in the same positions (in the same quadrants). In both the Spanish and the international communities the same *motor-theme* was treated (*group-decision-making*). In Figure 10 we compare the thematic networks of the *group-decision-making* theme. In it we can see there is almost no difference between both thematic networks, so it is possible to conclude that both communities are working on this theme, in the same way.

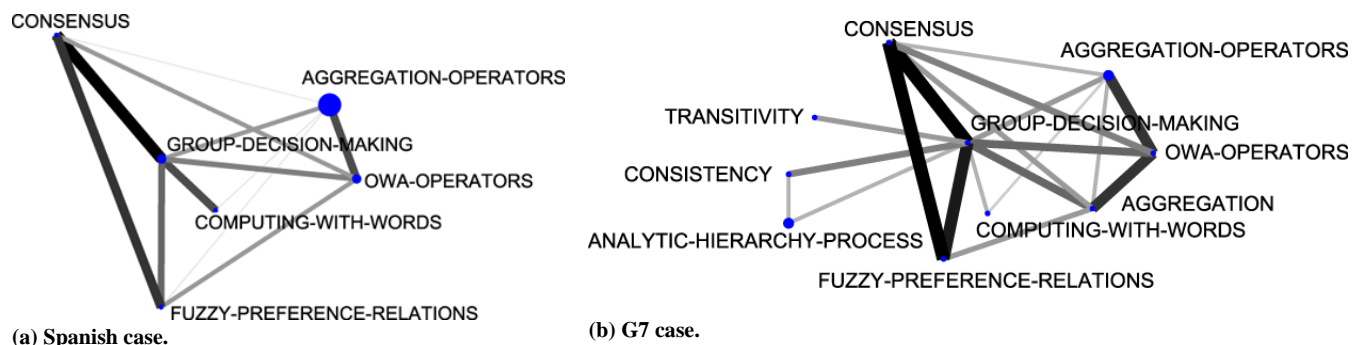


Figure 10: *Group-decision-making* thematic networks (sub-period 2004-2008).

Visibility of Spanish fuzzy set theory research in [ISI Web of Science](#)

The ISI Web of Science provides access to current and retrospective multidisciplinary information from approximately 8,700 of the most prestigious, high-impact research journals in the world. It also provides a unique search method, cited reference searching. With it, users can navigate forward and backward through the literature, searching all disciplines and time spans to uncover information relevant to their research. Users can also navigate to electronic full-text journal articles. In the link 'Advanced Search', we consider the query number 1 (see Section [Methods](#)), where only the Spanish papers were considered.

The query resulted in 1,442 papers, which, collectively, had received 13,843 citations, or 9.60 citations for each paper.

In Figure 11 we observe an increasing number of publications each year with more than 100 papers a year in recent years. In Figure 12 we observe that the number of citations shows a similar increasing trend in recent years. All these data can allow us to say the field of fuzzy set theory has now reached a stage of maturity after the earliest papers published at 1978; there are also many basic issues yet to be resolved and there is an active and vibrant worldwide community of researchers working on these issues.

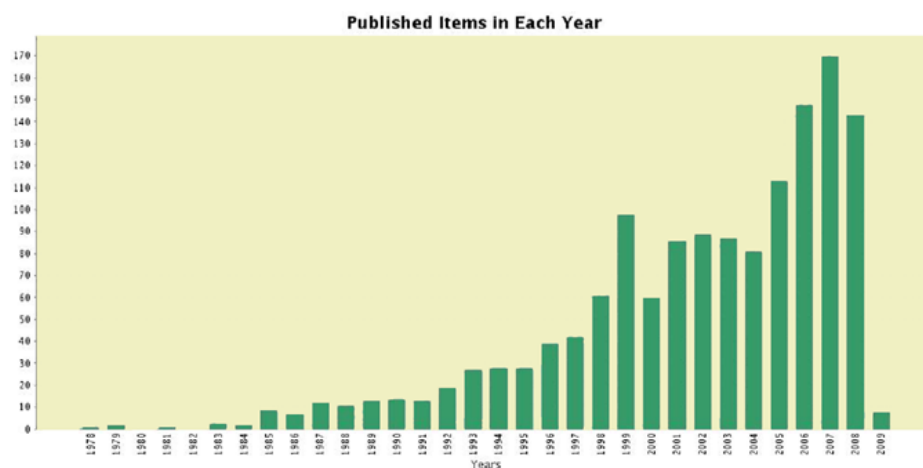


Figure 11: Number of published papers a year in Spain (ISI Web of Science).

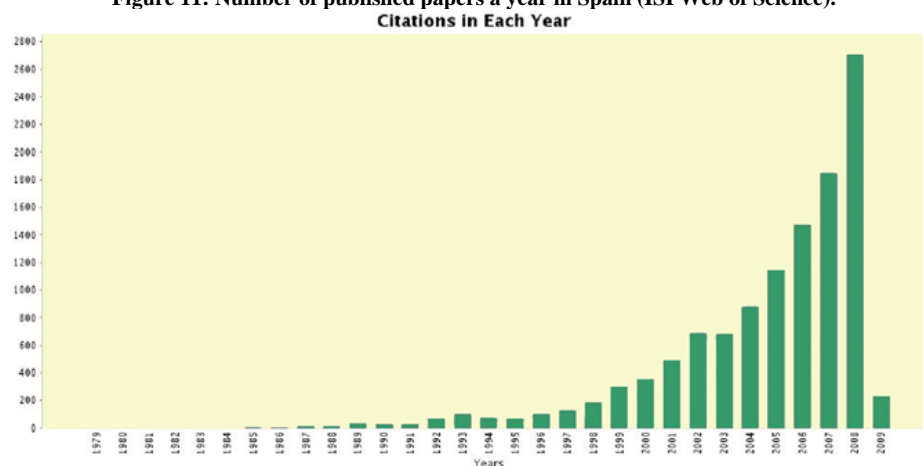


Figure 12: Number of citations a year in Spain (ISI Web of Science).

Doing a more detailed analysis, in Table 2, below, we show the most productive Spanish institutions (according to ISI Web of Science). In them we can distinguish the *University of Granada*, *University of Oviedo*, *University Complutense of Madrid*, *Consejo Superior de Investigaciones Científicas (CSIC)* and *Polytechnic University of Madrid* as the five most productive institutions in Spain. In [Appendix A](#), in Tables 5, 6, 7 and 8 more detailed information is shown for each sub-period.

Institution Name	Number of Papers
UNIV GRANADA	295
UNIV OVIEDO	142
UNIV COMPLUTENSE MADRID	77
CSIC	76
UNIV POLITECN MADRID	69
UNIV POLITECN CATALUNYA	62

UNIV JAEN	53
UNIV ROVIRA & VIRGILI	53
UNIV SANTIAGO DE COMPOSTELA	50
UNIV POLITECN VALENCIA	44
UNIV MURCIA	38
UNIV PUBL NAVARRA	38
UNIV PAIS VASCO	37
UNIV VALLADOLID	37
UNIV MALAGA	36
UNIV VALENCIA	29
UNIV GIRONA	23
UNIV SEVILLA	22
UNIV CARLOS III MADRID	21
UNIV CORDOBA	21

Table 2: The twenty most productive Spanish institutions from 1978 to 2008.

In [Appendix B](#), a study of the pioneering and the most cited papers in Spanish fuzzy community is presented.

Importance of Spanish fuzzy sets research community

Spain is one of the most active countries researching on fuzzy set theory; it is in seventh position in the ranking of the top ten most productive countries (as it could be observed in the ISI Web of Science using query number 1 on 7th January 2009). Spain is also one countries working on the topic for the longest period of time. Its first paper is from 1978, whereas other important countries on the topic published their first papers some years after, e.g., *Peoples Republic of China* (1980) or *Taiwan* (1983).

With respect to the institutions researching fuzzy set theory, in Table 3 below we can see that two Spanish institutions are in the top-twenty of the most productive. One of the Spanish institutions, the *University of Granada*, is the most active institution researching on the topic in the G7 group. Two Spanish institutions (*University of Granada* and *University of Oviedo*) were always active on the topic, as can be observed in [Appendix A](#) in Tables 9, 10, 11 and 2. In spite of Spain having published its first paper thirteen years after the first paper on the topic was published (1965), one Spanish institution reached seventh position of the most productive institutions in the first studied sub-period (1965-1993) (see [Table 9](#) in [Appendix A](#)). In addition, the *University of Granada* and the *University of Oviedo* were two of the three European institutions in those rankings (including the *University of Sheffield*).

Institution Name	Country	Numbers of papers
UNIV GRANADA	Spain	295
CITY UNIV HONG KONG	Peoples Republic of China	256
HONG KONG POLYTECH UNIV	Peoples Republic of China	243
IONA COLL	USA	209
UNIV ALBERTA	Canada	209
TSING HUA UNIV	Peoples Republic of China	207
UNIV ALABAMA	USA	181
SHANGHAI JIAO TONG UNIV	Peoples Republic of China	176
CHINESE ACAD SCI	Peoples Republic of China	162
HARBIN INST TECHNOL	Peoples Republic of China	160
UNIV TEXAS	USA	149
UNIV CALIF BERKELEY	USA	144
UNIV OVIEDO	Spain	142
TOKYO INST TECHNOL	Japan	137
PURDUE UNIV	USA	135
UNIV S FLORIDA	USA	131
UNIV MISSOURI	USA	130
UNIV SHEFFIELD	England (UK)	121
UNIV WATERLOO	Canada	121
UNIV TORONTO	Canada	120

Table 3: The twenty most productive international institutions from 1965 to 2008.

A deeper study shows us proof that Spanish institutions are leading, in recent years, some *motor-themes* as for example *group-decision-making*. Thus, twenty-three of the eighty-four published papers treating some aspect of this theme were published by Spanish researchers (i.e., about 27%), and 310 of

820 citations received by the theme were citations to Spanish papers, i.e., almost 38% of received citations. The eight most cited papers on this topic (Herrera-Viedma *et al.* 2004, Herrera-Viedma *et al.* 2005, Yager 2004, Xu 2004, Torra 2004, Xu and Da 2005, Xu and Chen 2007, Wang *et al.* 2005) are listed in Table 4 (where only papers with more than twenty-five citations are included; citation data were retrieved from the ISI Web of Science on September 21, 2009). This list includes three Spanish papers.

With respect to other non-motor-themes, the significance of the Spanish community is observed as about 10% in both published papers and citations. Thus, for example, in *neural-network*, a general and basic theme, forty-four of the 392 published papers were contributed by Spanish researchers (i.e., about 11%), and 253 of 2,357 cites got by the theme were cites to Spanish papers (i.e., about 11%).

All these data demonstrate that the Spanish fuzzy set theory research community is a very important community in this field.

Times cited	Publishing data & Institution / Country
92	Herrera-Viedma, E., Herrera, F., Chiclana, F., Luque, M. Some Issues on Consistency of Fuzzy Preference Relations. EUROPEAN JOURNAL OF OPERATIONAL RESEARCH 2004, 154:1, pp. 98-109. Univ Granada, Spain.
49	Herrera-Viedma, E., Martinez, L., Mata, F., Chiclana, F. A Consensus Support System Model for Group Decision-Making Problems With Multigranular Linguistic Preference Relations. IEEE TRANSACTIONS ON FUZZY SYSTEMS 2005, 13:5, pp. 644-658. Univ Granada, Spain and Univ Jaen, Spain and De Montfort Univ, England (UK).
41	Yager, R. R. Owa Aggregation Over a Continuous Interval Argument With Applications to Decision Making. IEEE TRANSACTIONS ON SYSTEMS MAN AND CYBERNETICS PART B-CYBERNETICS 2004, 34:5, pp. 1952-1963. Iona Coll, USA.
40	Xu, Z. S. Goal Programming Models for Obtaining the Priority Vector of Incomplete Fuzzy Preference Relation. INTERNATIONAL JOURNAL OF APPROXIMATE REASONING 2004, 36:3, pp. 261-270. Southeast Univ, Peoples R China.
30	Torra, V. Owa Operators in Data Modeling and Reidentification. IEEE TRANSACTIONS ON FUZZY SYSTEMS 2004, 12:5, pp. 652-660. CSIC, Spain.
29	Xu, Z. H., Da, Q. L. A Least Deviation Method to Obtain a Priority Vector of a Fuzzy Preference Relation. EUROPEAN JOURNAL OF OPERATIONAL RESEARCH 2005, 164:1, pp. 206-216. Southeast Univ, Peoples R China.
27	Xu ZS, Chen J An interactive method for fuzzy multiple attribute group decision making. INFORMATION SCIENCES 2007, 117:1, pp. 248-263. Tsing Hua Univ, Sch Econ & Management, Dept Management Sci & Engrn, Beijing, Peoples R China.
26	Wang Y. M., Yang H. B., Xu D. L. Two-Stage Logarithmic Goal Programming Method for Generating Weights From Interval Comparison Matrices. FUZZY SETS AND SYSTEMS 2005, 152:3, pp. 475-498. Univ Manchester, England (UK) and Fuzhou Univ, Peoples R China.

Table 4: The eight most cited papers in *group-decision-making* for sub-period 2004-2008.

Conclusions

In this paper, we have presented the first bibliometric study of fuzzy set theory research, focusing on the Spanish fuzzy sets research community. More than 16,344 original research papers have been processed. Based on this analysis, we have drawn the visual structure of fuzzy set theory research carried out by seven of the top-ten most productive countries on the topic.

The results also allow us to compare the Spanish community with the international community:

- Similar trends have been detected on the evolution of the fuzzy set theory field in both the Spanish and international cases. Data show that both the Spanish and the G7 communities are interested in the same or similar themes, as shown in *Spanish vs. international fuzzy set theory research*. This fact can be demonstrated, for example, with the data in Figure 10, which reveal the main keywords associated with the theme *group-decision-making* and the links among them. It can be that the thematic networks in Figure 10 maintain almost the same internal structure (same keywords, same links and same thickness of links).
- The Spanish community is an important collective working on fuzzy set theory. Two Spanish institutions always were in high positions in the ranking of the top-twenty of the most productive international institutions (see data in Tables 3, 9, 10, 11 and 12). This fact is also supported by observing that Spanish papers are working (and leading in recent years) some outstanding themes, for example the motor-theme *group-decision-making* (see Table 4).
- The most notable topics on fuzzy set theory in both Spanish and international communities can see grouped in (or related to):
 - theoretical aspects: *fuzzy-logic*, *connectives*, *uncertainty* and *OWA-operators*.
 - practical aspects: *group-decision-making*, *neural-networks*, and *design*.

Finally, we have to remark that the analysis is not without problems because of the bias implied. The most important caveat is that co-word analysis concentrates on priority themes and inevitably excludes those that have an anecdotal appearance. On the contrary, the analysis will legitimize discussion about general tendencies accepted by the majority of the scientific community. So, experts and novices can use these results and maps to know the current situation of the fuzzy set theory field.

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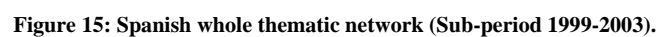
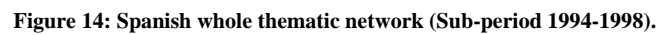
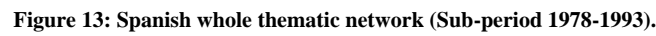
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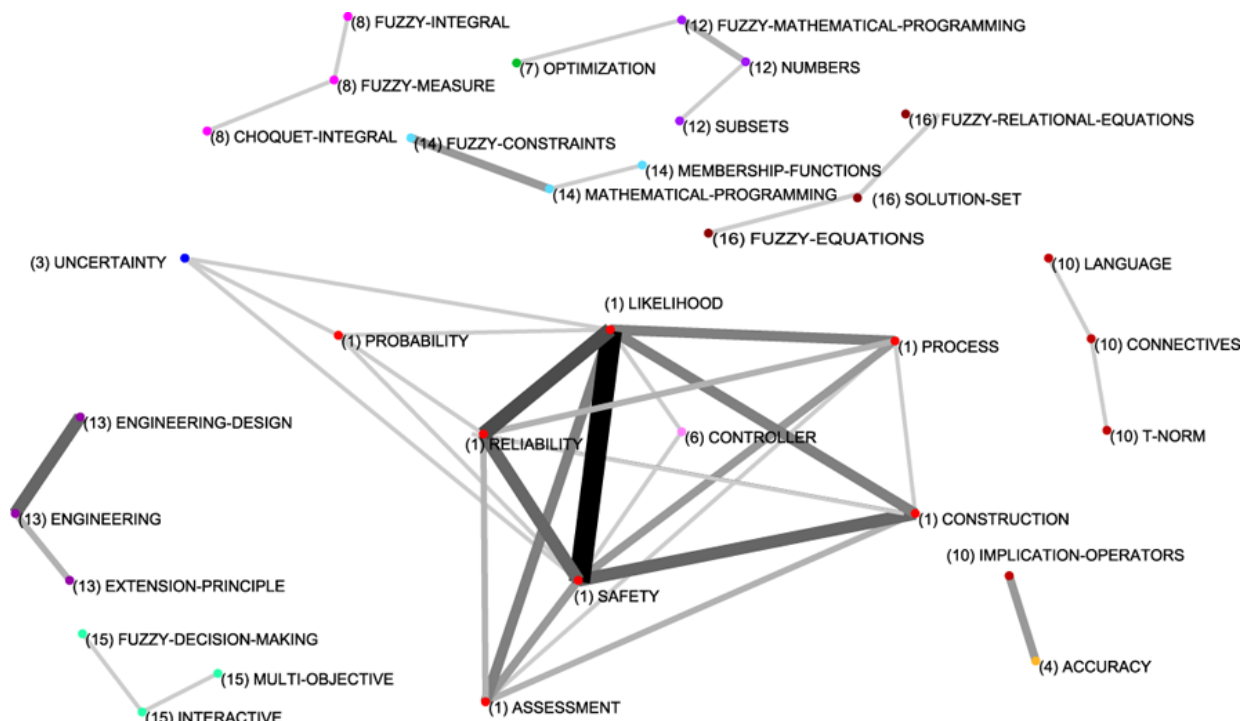
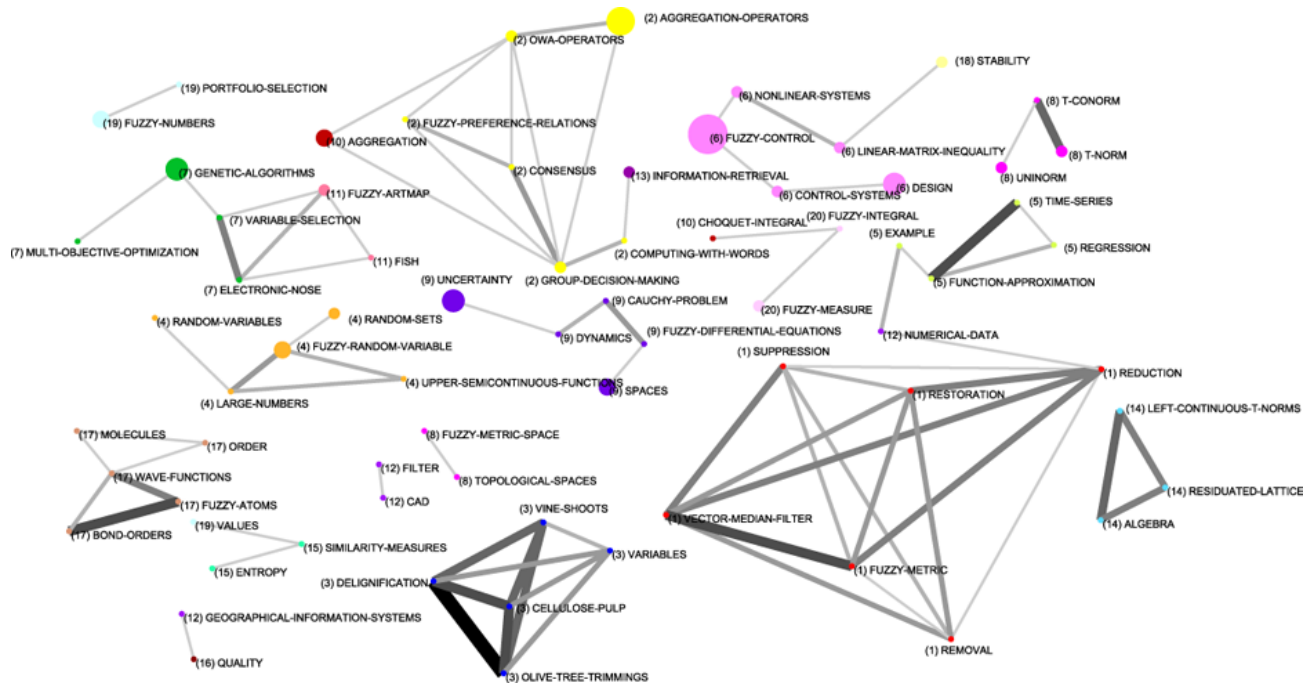
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Appendices

Appendix A





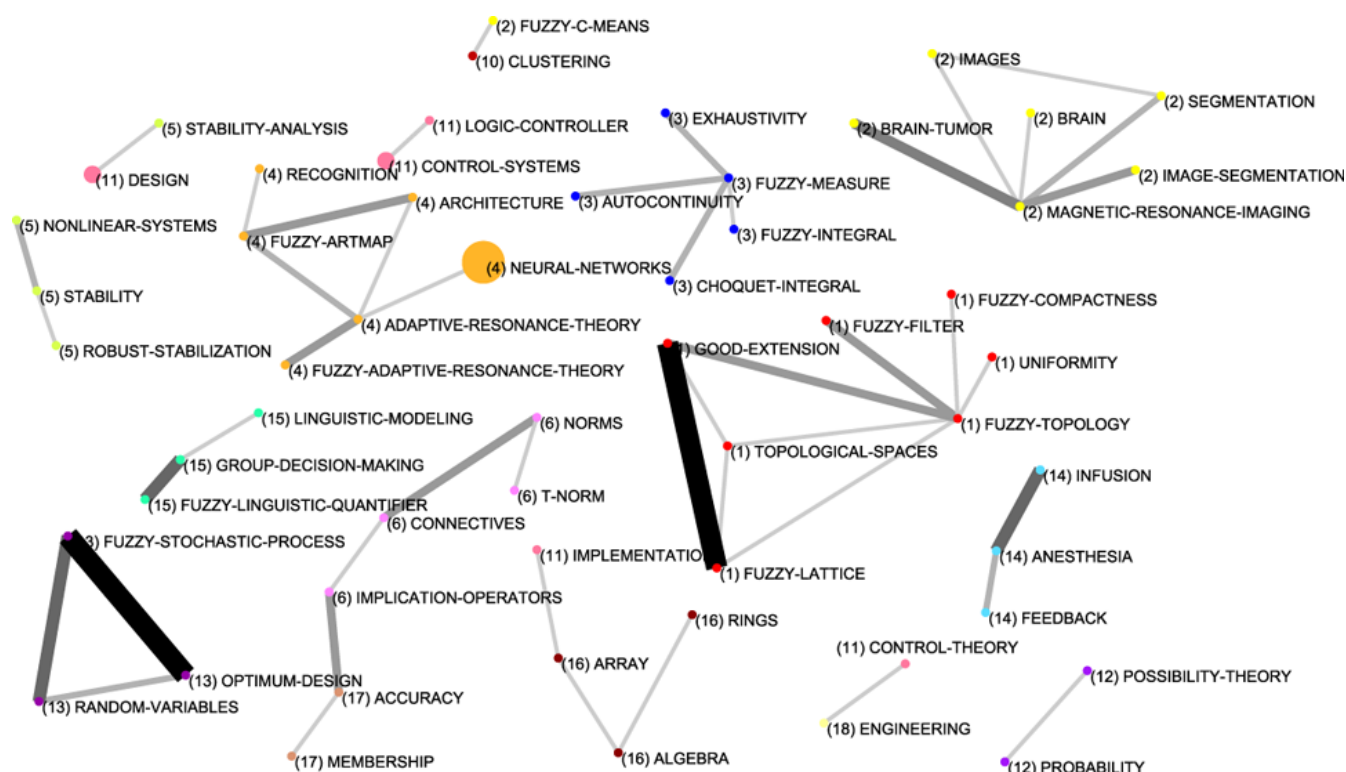


Figure 18: G7 whole thematic network (Sub-period 1994-1998)

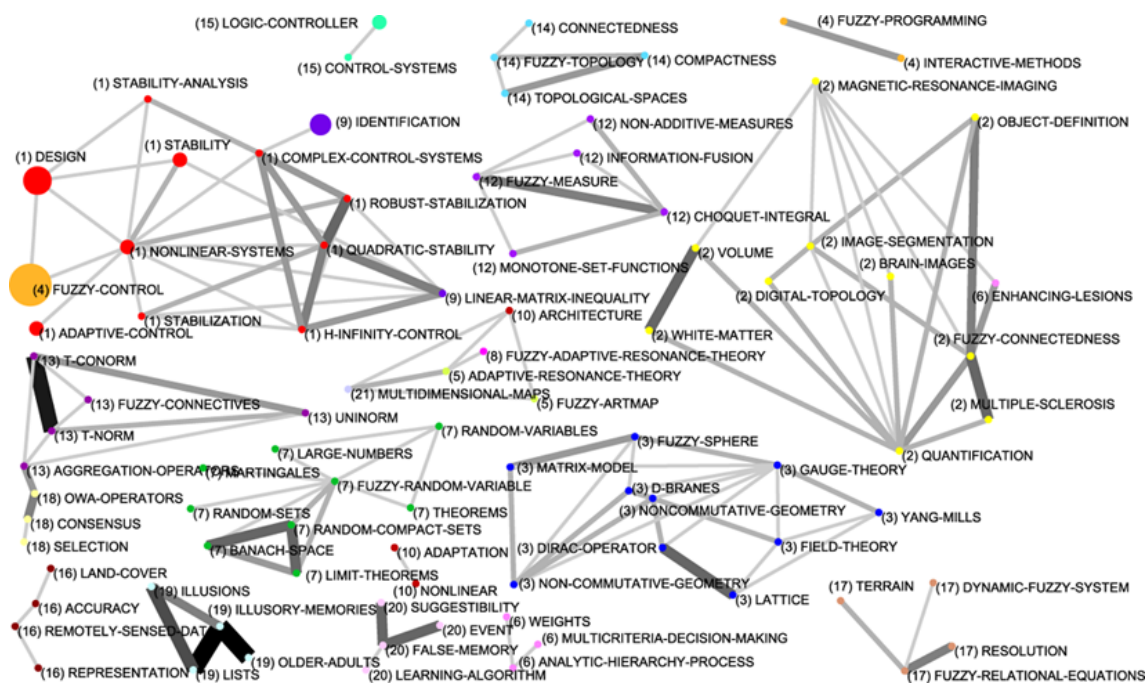


Figure 19: G7 whole thematic network (Sub-period 1999-2003).

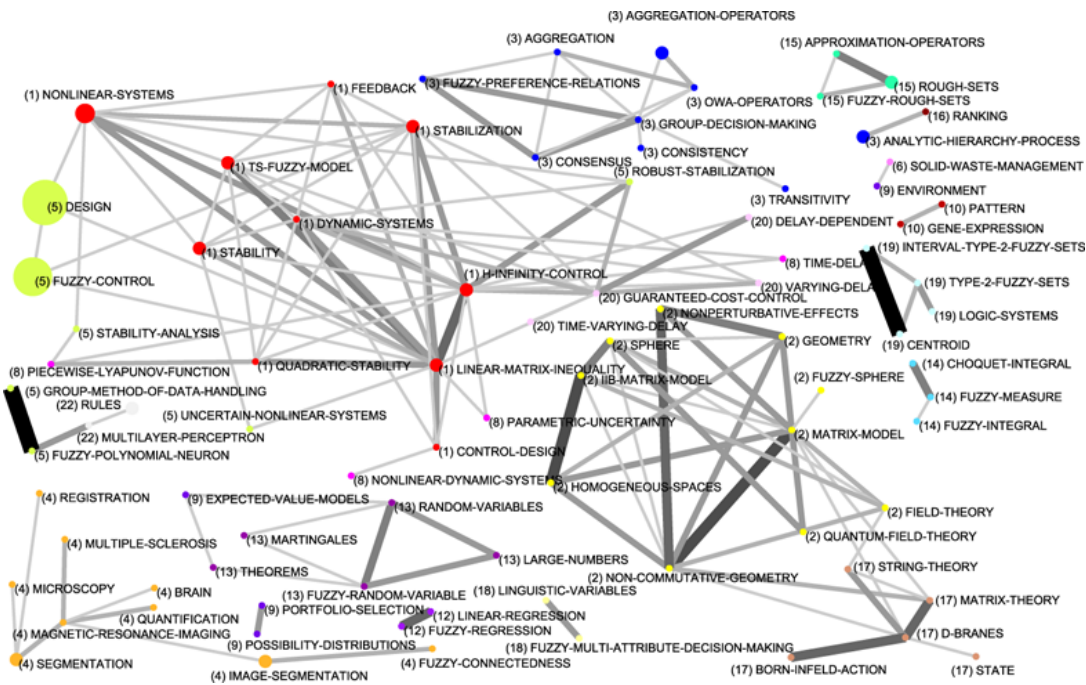


Figure 20: G7 whole thematic network (Sub-period 2004-2008)

Institution Name	Number of papers
UNIV GRANADA	39
UNIV OVIEDO	23
UNIV COMPLUTENSE MADRID	15
UNIV POLITECN MADRID	13
UNIV POLITECN CATALUNYA	11
UNIV SANTIAGO DE COMPOSTELA	10
UNIV PAIS VASCO	9
UNIV NAEL EDUC DISTANCIA	4
UNIV SANTIAGO	3
UNIV AUTONOMA MADRID	2
UNIV ILLES BALEARS	2
UNIV MURCIA	2
UNIV POLITECN BARCELONA	2
CLIN INFANTIL LA PAZ	1
COLEGIO UNIV SEGOVIA	1
CSIC	1
CTR ESTUDIS AVANCATS BLANES	1
ESCUELA TECH SUPER ARQUITECTURA BARCELONA	1
EU POLITECN CORDOBA	1
FAC INFORMAT BARCELONA	1

Table 5: The twenty most productive Spanish institutions in the sub-period 1978-1993.

Institution Name	Number of papers
UNIV GRANADA	62
CSIC	16
UNIV POLITECN MADRID	16
UNIV COMPLUTENSE MADRID	12
UNIV MURCIA	11
UNIV OVIEDO	11
PUBL UNIV NAVARRA	10

UNIV MALAGA	7
UNIV POLITECN CATALUNYA	6
UNIV SEVILLA	6
UNIV AUTONOMA BARCELONA	5
UNIV BASQUE COUNTRY	4
UNIV ROVIRA & VIRGILI	4
UNIV SANTIAGO DE COMPOSTELA	4
ESCUELA SUPER INGN	3
UNIV BARCELONA	3
UNIV PAIS VASCO	3
ETS ARQUITECTURA BARCELONA	2
ETS ARQUITECTURA VALLES	2
EUROPEAN SPACE TECHNOL CTR	2

Table 6: The twenty most productive Spanish institutions in the sub-period 1994-1998.

Institution Name	Number of papers
UNIV GRANADA	101
UNIV OVIEDO	40
CSIC	25
UNIV POLITECN CATALUNYA	23
UNIV POLITECN MADRID	20
UNIV ROVIRA & VIRGILI	20
UNIV MURCIA	19
UNIV JAEN	18
UNIV PUBL NAVARRA	17
UNIV MALAGA	16
UNIV SANTIAGO DE COMPOSTELA	14
UNIV VALLADOLID	14
UNIV COMPLUTENSE MADRID	13
UNIV SEVILLA	10
UNIV GIRONA	9
UNIV POLITECN VALENCIA	9
UNIV VALENCIA	9
UNIV CARLOS III MADRID	8
UNIV AUTONOMA MADRID	7
UNIV BALEARIC ISL	7

Table 7: The twenty most productive Spanish institutions in the sub-period 1999-2003.

Institution Name	Number of papers
UNIV GRANADA	93
UNIV OVIEDO	68
CSIC	34
UNIV JAEN	33
UNIV POLITECN VALENCIA	33
UNIV COMPLUTENSE MADRID	30
UNIV ROVIRA & VIRGILI	29
UNIV POLITECN MADRID	23
UNIV POLITECN CATALUNYA	22
UNIV SANTIAGO DE COMPOSTELA	22
UNIV VALLADOLID	20
UNIV ZARAGOZA	19
UNIV HUELVA	18
UNIV PAIS VASCO	18

UNIV VALENCIA	17
UNIV PUBL NAVARRA	16
UNIV ALCALA DE HENARES	15
UNIV CORDOBA	14
UNIV BASQUE COUNTRY	12
UNIV CARLOS III MADRID	12

Table 8: The twenty most productive Spanish institutions in the sub-period 2004-2008.

Institution Name	Number of papers
IONA COLL (USA)	76
UNIV ALABAMA (USA)	63
FLORIDA STATE UNIV (USA)	48
UNIV CALIF BERKELEY (USA))	48
TOKYO INST TECHNOL (Japan)	40
KANSAS STATE UNIV AGR & APPL SCI (USA)	39
UNIV GRANADA (Spain)	39
UNIV OSAKA PREFECTURE (Japan)	39
SICHUAN UNIV (Peoples R. of China)	33
UNIV MANITOBA (Canada)	29
UNIV ILLINOIS (USA)	28
UNIV MARYLAND (USA)	28
PURDUE UNIV (USA)	27
UNIV MISSOURI (USA)	25
UTAH STATE UNIV (USA)	25
UNIV TORONTO (Canada)	24
CREIGHTON UNIV (USA)	23
UNIV NEBRASKA (USA)	23
UNIV OVIEDO (Spain)	23
OSAKA UNIV (Japan)	21

Table 9: The twenty most productive internationals institutions for sub-period 1965-1993.

Institution Name	Number of papers
UNIV GRANADA (Spain)	62
UNIV MANITOBA (USA)	61
UNIV S FLORIDA (USA)	57
UNIV TEXAS (USA)	52
IONA COLL (USA)	46
UNIV ALABAMA (USA)	46
UNIV MISSOURI (USA)	42
UNIV ARIZONA (USA)	40
PURDUE UNIV (USA)	39
HIROSHIMA UNIV (Japan)	37
SUNY BINGHAMTON (USA)	37
TSING HUA UNIV (Peoples R. of China)	34
UNIV SHEFFIELD (England, UK)	34
TOKYO INST TECHNOL (Japan)	33
UNIV HOUSTON (USA)	31
UNIV CALIF BERKELEY (USA)	30
UNIV BRITISH COLUMBIA (Canada)	28
CREIGHTON UNIV (USA)	27
OSAKA UNIV (Japan)	27
UNIV TORONTO (Canada)	27

Table 10: The twenty most productive internationals institutions for sub-period 1994-1998.

Institution Name	Number of papers
CITY UNIV HONG KONG (Peoples R. of China)	116
UNIV GRANADA (Spain)	101
HONG KONG POLYTECH UNIV (Peoples R. of China)	96
TSING HUA UNIV (Peoples R. of China)	83
UNIV ALBERTA (Canada)	69
HARBIN INST TECHNOL (Peoples R. of China)	56
UNIV TEXAS (USA)	52
UNIV S FLORIDA (USA)	46
IONA COLL (USA)	45
CHINESE ACAD SCI (Peoples R. of China)	43
NAGOYA UNIV (Japan)	41
HUAZHONG UNIV SCI & TECHNOL (Peoples Rep. of China)	40
UNIV OVIEDO (Spain)	40
PURDUE UNIV (USA)	39
SHANGHAI JIAO TONG UNIV (Peoples R. of China)	39
UNIV ALABAMA (USA)	39
UNIV HONG KONG (Peoples R. of China)	39
BEIJING NORMAL UNIV (Peoples R. of China)	38
UNIV HOUSTON (USA)	38
HIROSHIMA UNIV (Japan)	37

Table 11: The twenty most productive internationals institutions for sub-period 1999-2003.

Institution Name	Number of papers
HONG KONG POLYTECH UNIV (Peoples R. of China)	140
CITY UNIV HONG KONG (Peoples R. of China)	131
UNIV ALBERTA (Canada)	126
SHANGHAI JIAO TONG UNIV (Peoples R. of China)	125
CHINESE ACAD SCI (Peoples R. of China)	107
UNIV GRANADA (Spain)	93
TSING HUA UNIV (Peoples R. of China)	90
XIAN JIAOTONG UNIV (Peoples R. of China)	76
UNIV WATERLOO (Canada)	71
UNIV OVIEDO (Spain)	68
HARBIN INST TECHNOL (Peoples R. of China)	65
NORTHEASTERN UNIV (USA)	55
ZHEJIANG UNIV (Peoples R. of China)	54
SHAANXI NORMAL UNIV (Peoples R. of China)	53
UNIV MANCHESTER (England, UK)	53
BEIJING NORMAL UNIV (Peoples R. of China)	52
DALIAN UNIV TECHNOL (Peoples R. of China)	49
HUAZHONG UNIV SCI & TECHNOL (Peoples R. of China)	47
UNIV CALGARY (Canada)	46
UNIV REGINA (Canada)	46

Table 12: The twenty most productive internationals institutions for sub-period 2004-2008.

Appendice B

1 Pioneering Spanish papers in the [ISI Web of Science](#)

Here we present the eight pioneer papers that introduced, from 1978 to 1984, fuzzy set theory in Spain:

- Trillas, E. and Riera, T. (1978). Entropies in finite fuzzy sets, *Information Sciences*, **15**(2), pp. 159-168.
- Batle, N. and Trillas, E. 1979 Entropy and fuzzy integral, *Journal of Mathematical Analysis and Applications*, **69**(2), 469-474.
- Ollero, A. and Freire, E. (1981). The structure of relations in personnel-management, *Fuzzy Sets and Systems*, **5**(2), 115-125.

- Vila, M. A. and Delgado, M. (1983). On medical diagnosis using possibility measures, *Fuzzy Sets and Systems*, **10**(3), 211-222.
- Alsina, C. and Trillas, E. and Valverde, L. (1983). On some logical connectives for fuzzy-sets theory, *Journal of Mathematical Analysis and Applications*, **93**(1), 15-26.
- Vila, M. A. and Delgado, M. (1983). Problems of classification in a fuzzy environment, *Fuzzy Sets and Systems*, **9**(3), 229-239.
- Gil, M. A. and Lopez, M. T. and Gil, P. (1984). Comparison between fuzzy information systems, *Kybernetes*, **13**(4), 245-251.
- Verdegay, J. L. (1984). A dual approach to solve the fuzzy linear-programming problem, *Fuzzy Sets and Systems*, **14**(29), 131-141.

2 The eight most cited Spanish papers in the [ISI Web of Science](#)

The search on the [ISI Web of Science](#) allows us to find the eight most cited Spanish papers that can provide a picture on eight important contributions on the topic that are representative approaches of different areas. Figure 21 shows the list of eight papers and they are briefly described below.

	2005	2006	2007	2008	2009	Total	Average Citations per Year
Use the checkboxes to remove individual items from this Citation Report or restrict to items processed between 1900-1914 and 2008 Go	1155	1484	1865	2719	2243	13,838	432.44
Title: Monoidal t-norm based logic: towards a logic for left-continuous t-norms Author(s): Esteve F, Godo L Conference Information: 5th International Conference on Fuzzy Sets Theory and its Applications (FSTA 2000), JAN 31-FEB 04, 2000 LIPTOVSKY, CZECH REPUBLIC Source: FUZZY SETS AND SYSTEMS Volume: 124 Issue: 3 Special Issue: Sp. Iss. SI Pages: 271-288 Published: DEC 16 2001	28	30	43	50	26	213	23.67
Title: Linguistic decision analysis: steps for solving decision problems under linguistic information Author(s): Herrera F, Herrera-Viedma E Source: FUZZY SETS AND SYSTEMS Volume: 115 Issue: 1 Pages: 67-82 Published: OCT 1 2000	13	31	33	52	41	188	18.80
Title: A 2-tuple fuzzy linguistic representation model for computing with words Author(s): Herrera F, Martínez L Source: IEEE TRANSACTIONS ON FUZZY SYSTEMS Volume: 8 Issue: 6 Pages: 746-752 Published: DEC 2000	17	17	27	55	40	175	19.44
Title: FUZZY-LOGIC CONTROLLERS ARE UNIVERSAL APPROXIMATORS Author(s): CASTRO JL Source: IEEE TRANSACTIONS ON SYSTEMS MAN AND CYBERNETICS Volume: 25 Issue: 4 Pages: 629-635 Published: APR 1995	20	11	17	14	8	168	11.20
Title: Integrating three representation models in fuzzy multipurpose decision making based on fuzzy preference relations Author(s): Chiclana F, Herrera F, Herrera-Viedma E Source: FUZZY SETS AND SYSTEMS Volume: 97 Issue: 1 Pages: 33-48 Published: JUL 1 1998	13	26	35	40	22	165	13.75
Title: ON THE STRUCTURE OF F-INDISTINGUISHABILITY OPERATORS Author(s): VALVERDE L Source: FUZZY SETS AND SYSTEMS Volume: 17 Issue: 3 Pages: 313-328 Published: DEC 1985	9	12	14	23	17	163	6.79
Title: A model of consensus in group decision making under linguistic assessments Author(s): Herrera F, Herrera-Viedma E, Verdegay JL Source: FUZZY SETS AND SYSTEMS Volume: 78 Issue: 1 Pages: 73-87 Published: FEB 26 1996	15	23	18	41	21	157	11.21
Title: ON SOME LOGICAL CONNECTIVES FOR FUZZY-SETS THEORY Author(s): ALSINA C, TRILLAS E, VALVERDE L Source: JOURNAL OF MATHEMATICAL ANALYSIS AND APPLICATIONS Volume: 93 Issue: 1 Pages: 15-26 Published: 1983	9	7	1	10	7	136	5.04

Figure 21: The eight Spanish most cited papers ([ISI Web of Science](#)).

- Esteve, F. and Godo, L. (2001) [213 citations]. Monoidal t-norm based logic: towards a logic for left-continuous t-norms, *Fuzzy Sets and Systems*, **124**(3), 271-288.

In this paper MTL-algebras are investigated.

- Herrera, F. and Herrera-Viedma, E. (2000) [188 citations]. Linguistic decision analysis: steps for solving decision problems under linguistic information, *Fuzzy Sets and Systems*, **115**(1), 67-82.

This paper describes the key steps for solving decision making problems with linguistic information. This paper became in a reference paper in *decision-making* and *group-decision-making*.

- Herrera, F. and Martínez, L. (2000) [175 citations]. A 2-tuple fuzzy linguistic representation model for computing with words, *IEEE Transactions on Fuzzy Systems*, **8**(6), 746-752.

This paper presents a new fuzzy linguistic approach based on 2-tuple linguistic values.

This paper become in a reference point in *group-decision-making*, which was a *motor-theme* in both Spanish and G7 cases in the period 1999-2008.

- Castro, J.L. (1995) [168 citations]. Fuzzy-logic controllers are universal approximators, *IEEE Transactions on Systems Man and Cybernetics*, **25**(4), 629-635.

This was an important paper in the 1990s, where the interest for developing the theoretical foundations of fuzzy control was very important, because of the great applicability of these models.

- Chiclana, F., Herrera, F. and Herrera-Viedma, E. (1998) [165 citations]. Integrating three representation models in fuzzy multipurpose decision making based on fuzzy preference relations, *Fuzzy Sets and Systems*, **97**(1), 33-48.

This paper presents the possibility of merging three commonly-studied representation models for solving decision making problems.

- Valverde, L. (1985) [163 citations]. On the structure of F-indistinguishability operators, *Fuzzy Sets and Systems*, **17**(3), 313-328.

This paper is focused on indistinguishability operators and fuzzy operators and, therefore, it is also included in the theme *T-norm*, it used t-norms and t-conorms in the study.

- Herrera F., Herrera-Viedma E., and Verdegay J.L. (1996) [157 citations]. A model of consensus in group decision making under linguistic assessments, *Fuzzy Sets and Systems*, **78**(1), 73-87.

This paper presents a consensus model in group decision making under linguistic assessments. This paper was included in the *group-decision-making* thematic network, a motor theme from 1993.

- Alsina, C. and Trillas, E. and Valverde, L. (1983) [136 citations]. On some logical connectives for fuzzy-sets theory, *Journal of Mathematical Analysis and Applications*, **93**(1), 15-26.

This paper is included in the theme connectives, such as it proposes a family of connectives using several t-norms and t-conorms.

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