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A bibliometric study about the research based on hybridating the fuzzy logic field and the other computational intelligent techniques: A visual approach

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Abstract. In this paper, a bibliometric study on the interconnections between the fuzzy logic theory field and the other soft-computing techniques is presented. Bibliometric maps showing the associations between the main concepts between these research fields are provided for the periods 1990–1999, 2000–2003, and 2004–2007. The maps provide insight into the structure of these fields. They visualize the division of the field into several subfields and they indicate the relations between these subfields. The maps are created by co-word analysis. Experts can use these maps to forecast emerging trends for hybrid intelligent systems.

1. Introduction

The term Soft-Computing (SC) refers to a family of computing techniques that, when Zadeh introduced the topic [13], originally comprised four different partners: *fuzzy logic*, *evolutionary computation*, *neural networks*, and *probabilistic reasoning*. The term SC distinguishes these techniques from hard computing that is considered less flexible and computationally demanding. The key point of the transition from hard to SC is the observation that the computational effort required by conventional computing techniques sometimes is so hard. Furthermore, it is also unnecessary since in many applications precision can be sacrificed in order to accomplish more economical, less complex and more feasible solutions. Imprecision results from our limited capability to resolve detail and encompass the notions of partial, vague, noisy and incomplete information about the real world. In other words, it becomes not only difficult or even impossible, but also inappropriate to apply hard computing techniques when dealing with situations in which uncertainty and imprecision are involved. According to Zadeh [14], the guiding principle of SC is to exploit the tolerance for imprecision, uncertainty, partial truth, and approximation to achieve tractability, robustness, low cost solution and better rapport with reality. All the methodologies that constitute the realm of SC are considered complementary as desirable features lacking in one approach are present in another [2]. Hence, the SC framework is put into effect by hybrid systems combining two or more of the constituent technologies with complementary characteristics.

In this paper, a bibliometric study on hybrid approaches using fuzzy logic and other SC techniques is presented. This hybrid SC and fuzzy logic field will be called in this paper FL-SC field. Specifically, it is composed of the hybridizations between the *Fuzzy Logic* topic and the *Evolutionary Algorithms*, *Neural Networks* and *Swarm Intelligence* topics.

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The bibliometric study is done by means of bibliometric maps that show the associations between the main concepts studied by the FL-SC community. The maps provide insight into the structure of the FL-SC field, visualize the division of the field into several subfields and indicate the relations between these subfields. More concretely, we will study the FL-SC field using the concept of longitudinal mapping, introduced by Garfield [8]. In longitudinal mapping, a series of chronologically sequential maps can be used to detect the advances of scientific knowledge and the evolution of the field over the last few years. While maps of current data alone cannot predict where research will go, longitudinal maps can be useful indicators in the hands of informed analysts and domain experts. Analysts and domain experts can use longitudinal maps to forecast emerging trends for a subject domain. Since domain visualizations typically reference key works in a field, they are a good tool to enable the novice to become instantly familiar with a field through easy identification of key topics and theirs relationships. The bibliometric maps are created by co-word analysis [4, 6,12], where selected original papers from ISI Web of Science (ISIWoS) [9] are used.

This paper is organized as follows. Section 2 introduces the co-word analysis methodology. Section 3 describes the visual evolution of the FS-SC field. Section 4 summarizes some important results. Finally, in Section 5 some conclusions are drawn.

2. The Co-Words Analysis: Methodology

Co-word analysis is a content analysis technique that is effective in mapping the strength of association between information items in textual data [4,6,12]. It is a powerful technique for discovering and describing the interactions between different fields in scientific research [1,7]. Co-word analysis reduces a space of descriptors (or keywords) to a set of network graphs that effectively illustrate the strongest associations between descriptors.

This technique illustrates associations between keywords by constructing multiple networks which highlight associations between keywords, and where associations between networks are possible.

The basic assumption in bibliometric mapping [3] is that each research field can be characterized by a list of important keywords. Each publication in the field can be characterized by a sub-list of these global keywords. Such sub-lists are like DNA fingerprints of these published articles. By matching keyword-based fingerprints, one can measure the similarity between a pair of publications. 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. Following the DNA metaphor, if two publications fingerprints are similar enough, they are bound to come from the same species. In [11] Noyons et. al. incorporate performance assessment into the creation of bibliometric maps in order to measure the impact level of different sub-fields and themes and to address strategic questions such as: who is where in the subject domain, and how strong is their research?

According to Börner et al. [3], 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 analyze, (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 the way in which we implement each of these steps in this paper.

First: Collection of raw data. In this paper, the raw data consist of a corpus containing 5220 original papers about the FL-SC research field which are extracted from the Web of Science database [9] with the query #1 on 1th October 2008 using the keywords listed in Table 1:

```
query #1: TS=(fuzzy* AND ("neural network*" OR
"back-propagation" OR backpropagation OR "back propagation"
OR "multilayer perceptron" OR "multi-layer perceptron" OR
"connectionist system*" OR "radial basis function" OR
"genetic algorithm*" OR "evolution strateg*" OR
"evolutionary strateg*" OR "evolution algorithm*" OR
"evolutionary algorithm*" OR "evolution computation" OR
"evolutionary computation" OR "evolution optimization" OR
"evolutionary optimization" OR "evolution optimisation" OR
"evolutionary optimisation" OR "differential evolution" OR
"genetic programming" OR "evolution programming" OR
"evolutionary programming" OR "coevolution" OR
"ant colony system*" OR "ant colony optimization" OR
"ant colony optimisation" OR "ant system" OR
"swarm intelligence" OR "particle swarm optimization" OR
"particle swarm optimisation"))AND Document Type=(Article).
```

In Fig. 1 the number of FL-SC original papers in ISIWoS from 1990 to 2007 is shown.

Three sets of data are collected, one for each studied subperiod: 1990–1999[1], 2000–2003, 2004–

[1] In co-word analysis, in a longitudinal study, it is usual the first subperiod has to be the most long lasting one to get the same number of published papers.

Table 1
Original papers per topic in ISIWoS (1990–2007)

TOPICS	KEYWORDS	PAPERS
NEURAL NETWORK & FUZZY	"neural network*", "back-propagation", "backpropagation", "back propagation", "multilayer perceptron", "multi-layer perceptron", "connectionist system*", "radial basis function"	4.474
EVOLUTIONAY ALGORITHMS & FUZZY	"evolution strateg*", "evolutionary strateg*", "evolution algorithm*", "evolutionary algorithm*", "evolution computation", "evolutionary computation", "evolution optimization", "evolutionary optimization", "evolution optimisation", "evolutionary optimisation", "differential evolution", "genetic programming", "evolution programming", "evolutionary programming", "genetic algorithm*", "coevolution"	1.595
SWARM INTELLIGENCE & FUZZY	"ant colony system*", "ant colony optimization", "ant colony optimisation", "ant system", "swarm intelligence", "particle swarm optimization", "particle swarm optimisation"	101

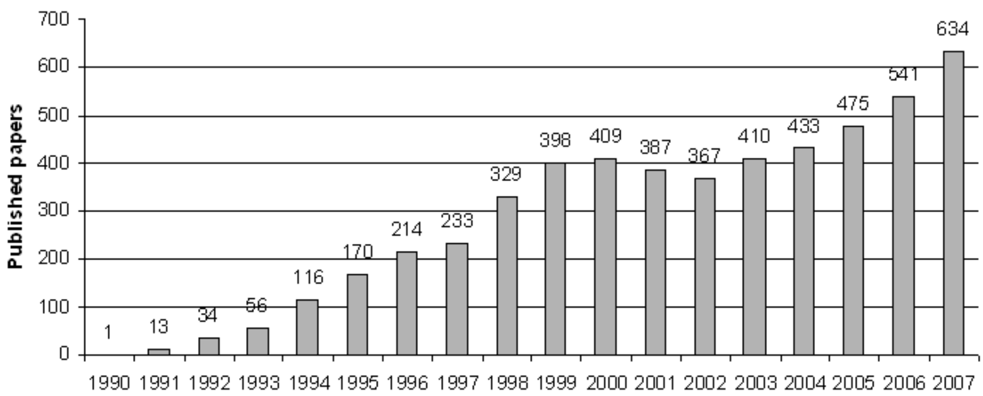


Fig. 1. FL-SC papers in ISIWoS from 1990 to 2007.

2007. In this way, separate bibliometric maps can be constructed for each of the three subperiods. The number of papers per subperiod are shown in Fig. 2.

Second: Selection of the type of item to analyze. According to Börner et al. [3], journals, papers, authors, and descriptive terms or words are most commonly selected as the type of item to analyze. In this paper, we choose to analyze descriptive words, and more concretely, keywords. A bibliometric map showing the associations between keywords in a scientific field is referred to as a keywords based map in this paper.

Third: Extraction of relevant information from the raw data collected in the first step. In this paper, the relevant information consists of the co-occurrence frequencies of keywords. The co-occurrence frequency of two keywords is extracted by counting the number of papers in which the two keywords both occur in the keywords section.

Fourth: Calculation of similarities between items based on the information extracted in the third step. In this paper, similarities between items are calculated based on 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 [10], $e_{ij} := \frac{c_{ij}^2}{c_i \cdot c_j}$, 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 1; when they are never associated, it equals 0. Once the links are quantified, groupings or themes, consisting of more strongly linked networks that represent the centers of interest of the researchers, are produced by an algorithm called *simple centers*.

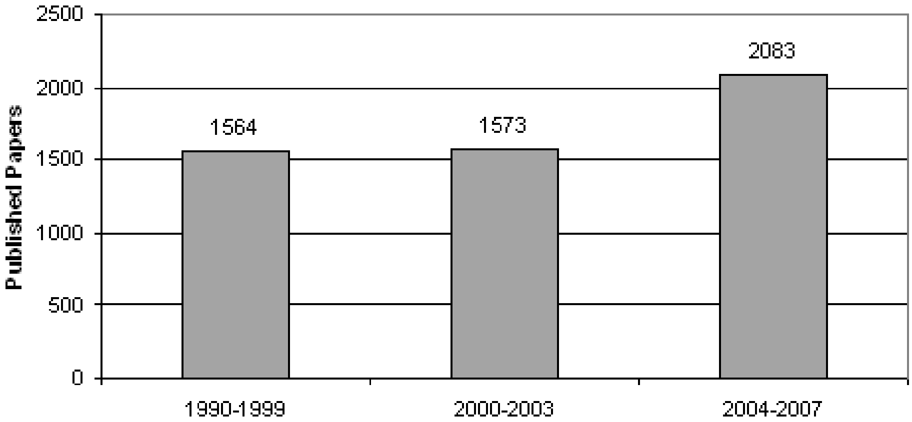


Fig. 2. FL-SC papers per subperiod.

As described in [4], the simple centers algorithm runs twice through the data to produce the desired networks. The first pass constructs the networks depicting the strongest associations, links added in this pass are called internal links. The second run adds links of weaker strengths to these networks which form associations between networks. The links added during the second pass are called external links.

Note that two keywords that appear infrequently in the corpus but always appear together will have larger strength values than keywords that appear many times in the corpus almost always 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[2] are considered potential links while building networks during the first pass of the algorithm.

During the first pass, the link that has the largest 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 largest 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 and is defined as: $c = 10 * \sum e_{kh}$, with k being a keyword belonging to the theme and h being a keyword belonging to other themes.

The *density* of a network measures the internal strength of the network and is defined as: $d = 100\frac{\sum e_{ij}}{w}$, with i and j keywords belonging to the theme and w el 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.

Density and centrality measures are used in the sixth step for visualizing the thematic networks in a low-dimensional space.

As described in [4], the algorithm for the generation of the networks is as follows:

1. Select a minimum for the number of co-occurrences, c_{ij}, for keywords i and j, select maxima for the number of pass-1 links, and select maxima for the total (pass-1 and pass-2) links.
2. Start pass-1;
3. Generate the highest e_{ij} value from all possible keywords to begin a pass-1 network;
4. From that link, form other links in a breadth-first manner until no more links are possible due to the co-occurrence minima or to pass-1 link or node maxima. Remove all incorporated keywords from the list of subsequent available pass-1 keywords;

[2] Minimum occurrence and co-occurrence values are 7 and 3 respectively for each subperiod. This is done by taking into account the distribution of frequencies and co-occurrences of keywords.

5. Repeat steps 3 and 4 until all pass-1 networks are formed; i.e., until no two remaining keyword pairs co-occur frequently enough to begin a network;
6. Start pass-2;
7. Restore all pass-1 keywords to the list of available keywords;
8. Start with the first pass-1 network.
9. Generate all links to pass-1 nodes in the current network to any pass-1 nodes having at least the minimal co-occurrences in descending order of e_ij value; stop when no remaining keyword pairs meet the co-occurrence minima, or when the total link maxima is met. Do not remove any keyword from the available list;
10. Select the next succeeding pass-1 network, and repeat step 9.

Fifth: Positioning of items in a low-dimensional space based on the similarities calculated in the fourth step. In this paper, the low-dimensional space is referred as a keywords based map and only two-dimensional keywords based maps are considered. The two considered 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 cr and dr values.

Sixth: Visualization of the low-dimensional space that results from the fifth step. In our study, we use the CoPalRed [5] computer program, which visualizes the networks in a strategic diagram. A strategic diagram of the network is presented in Fig. 3. The abscissa axis is centrality, or the external cohesion index. It represents the most or least central position within the overall network. The ordinate axis is density, or the index of internal cohesion. It represents the conceptual development of the theme. Papers in the upper-right quadrant (quadrant 1) are considered motor themes of the speciality, given that they present strong centrality and high density. Those of the lower-right quadrant (quadrant 2) are the most general basic themes, although with internal development not as high as those of quadrant 1. The themes of quadrant 3 (upper-left) are very specialized, but peripheral in character, while those of the lower-left (quadrant 4), with low density and little centrality, mainly represent either emerging or disappearing themes. CoPalRed [5] visualizes a keywords based map by displaying a label for each keyword that indicates the location of the theme in the strategic diagram. As an example, in the strategic diagram in Fig. 3, 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.

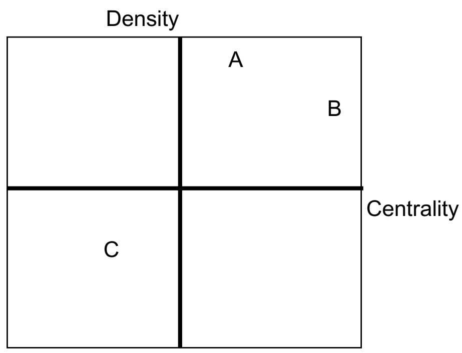


Fig. 3. A example of strategic diagram.

3. Visual Evolution of the FL-SC Field

To analyze the evolution of the FL-SC field over the last eighteen years (1990–2007), four studies are performed in following subsections. In Subsection 3.1 the whole FL-SC field is analyzed. Sections 3.2, 3.3 and 3.4 analyze separately the relationship between the *Fuzzy Logic* topic and the *Neural Networks*, *Evolutionary Algorithms*, and *Swarm Intelligence* topics.

3.1. Analyzing the whole FL-SC field

To analyze the evolution of the whole FL-SC field over the last eighteen years, strategic diagrams for the three studied subperiods (1990-1999, 2000–2003 and 2004–2007) are shown in Figs 4 and 5. The volume of the spheres is proportional to the number of documents corresponding to each theme in each studied subperiod. In the following the three subperiods are described.

In the first subperiod (1990–1999), the longer one, in which 1535 original papers were published, the most

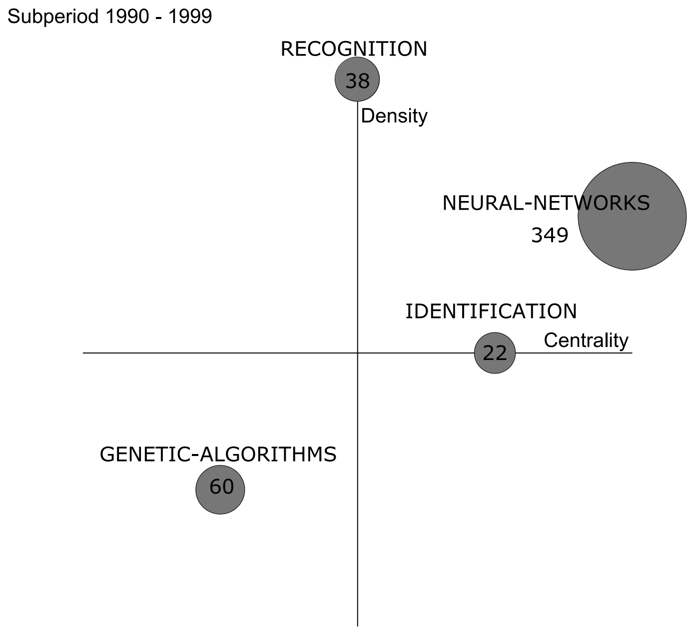


Fig. 4. FL-SC strategic diagram for the subperiod 1990–1999.

important themes in the whole FL-SC field, in relative weight in terms of number of documents, were: *NEURAL-NETWORK* (349 papers[3]) and *GENETIC-ALGORITHMS* (60 papers) (see Fig. 4). Because of its strategic situation (upper-right quadrant), the theme *NEURAL-NETWORK* is supposed very conceptually developed, whereas *GENETIC-ALGORITHMS* (lower-left quadrant) is considered as an incipient discipline, in development process in the FL-SC field.

In the second subperiod (2000–2003), with 1573 papers, *NEURAL-NETWORK* (891 papers), *GENETIC-ALGORITHMS* (256 papers) and *RULE-GENERATION* (63 papers) were the most studied themes (in terms of number of documents). *NEURAL-NETWORK* was the most developed theme (upper-right quadrant). The theme was supported by 891 papers, i.e., near of 57% of papers in those years treated some aspects of neural-networks (see Fig. 5a).

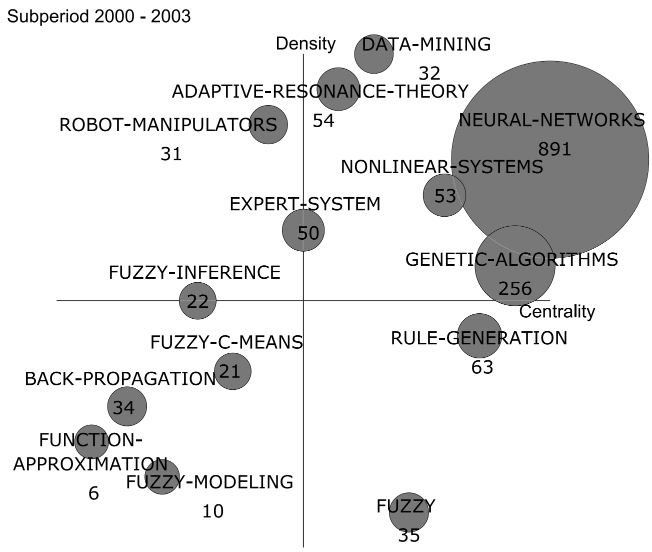
From 2004–2007, the three most studied themes (see Fig. 5b) were: *NEURAL-NETWORK* (358 papers), *FUZZY-CONTROL* (43 papers), and *OPTIMIZATION* (36 papers). *NEURAL-NETWORK*, sited in the upper-right quadrant of the strategic diagram for this subperiod, was supposed quite related externally to concepts applicable to other themes that were conceptually closely related.

[3]CoPalRed assumes a paper belong to a theme when it presents at least 2 keywords of the theme.

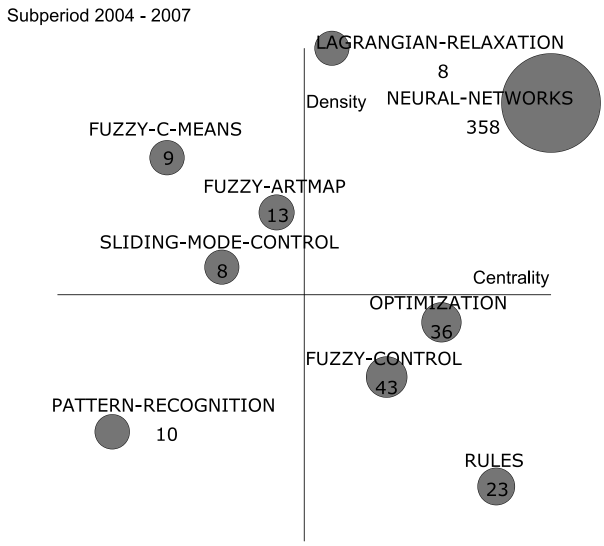
From Figs 4 and 5 we can appreciate several conclusions in the evolution of the most long-lasting themes in the whole FL-SC based research field:

- *NEURAL-NETWORK* has been the most long-lasting theme in the last eighteen years.
- *NEURAL-NETWORK* has been the most important topic in the FL-SC field. It has grouped almost 1600 original papers from 1990 to 2007. In addition, *NEURAL-NETWORK* has always been sited in the upper-left quadrant. So, it can be said *NEURAL-NETWORK* is the "motor-theme" in the FL-SC based research field.
- The theme *GENETIC-ALGORITHMS*, that in 1990–1999 was considered as an incipient theme (lower-left quadrant), became in a very central and dense theme from 2000 to 2003. In the last four years (2004–2007) it was absorbed by the theme *NEURAL-NETWORK* (see thematic network[4] in Fig. 6). It might mean the FL-SC research community is developing "multi-hybrid" intelligent systems combining several aspect of the subfields *Neural Networks, Evolutionary Algorithms* and *Fuzzy*.

[4]In these thematic 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}.



(a) Period 2000-2003.



(b) Period 2004-2007.

Fig. 5. FL-SC strategic diagrams for the subperiods 2000–2003 and 2004–2007.

In Fig. 6 the thematic network of the theme *NEURAL-NETWORK* is shown. It shows the topics which the theme was related in the last subperiod (2004–2007). In this subperiod the theme *NEURAL-NETWORK* had a strong relation with the topic *FUZZY-LOGIC* (see the thick line between both). Other important related subthemes were *NEURO-FUZZY-SYSTEMS* and *GENETIC-ALGORITHMS*. On the other hand, this thematic network indicates the theme *NEURAL-NETWORK* was used in problems related with classification, prediction and identification.

3.2. Analyzing the hybridization between the neural networks and the Fuzzy fields

From query #1 in Section 2, 4474 papers on Neural Networks and Fuzzy (NNs-FL) hybrid intelligent systems were downloaded from ISIWoS database [9]. In the first subperiod (1990–1999), the most important themes in the NNs-FL subfield, in relative weight in terms of number of documents, were: *NEURAL-NETWORK* (327 papers), *RECOGNITION* (38 papers) and *IDENTIFICATION* (32 papers) (see Fig. 7a). Because of their strategic situation (upper-right quadrant),

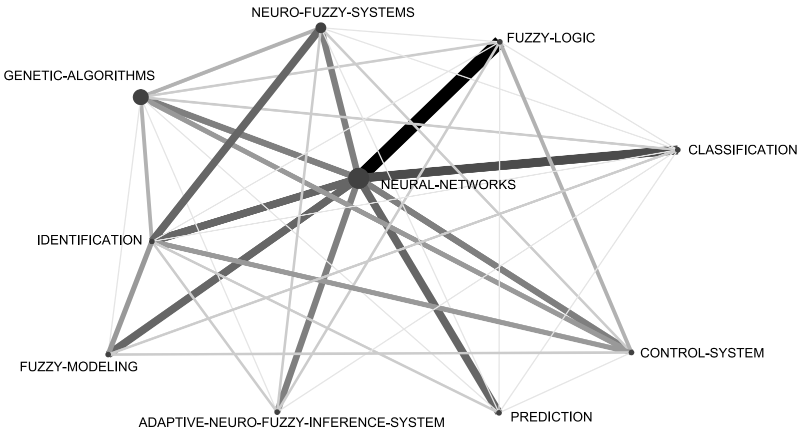
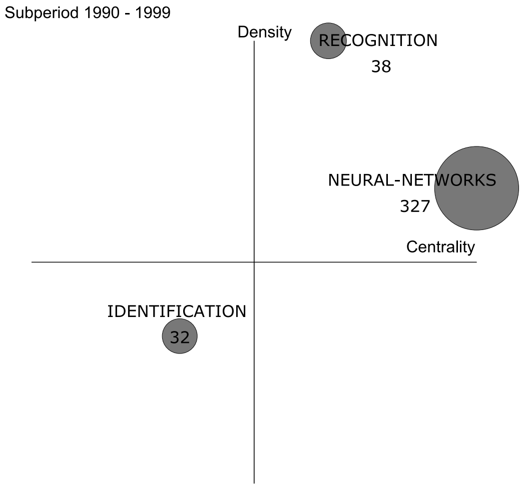
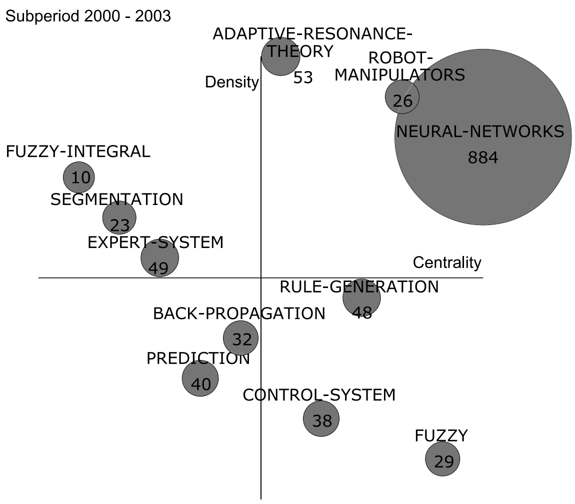


Fig. 6. The *NEURAL-NETWORK* thematic network (subperiod 2004–2007).



(a) Period 1990-1999.



(b) Period 2000-2003.

Fig. 7. NNs-FL strategic diagrams for the subperiods 1990–1999 and 2000–2003.

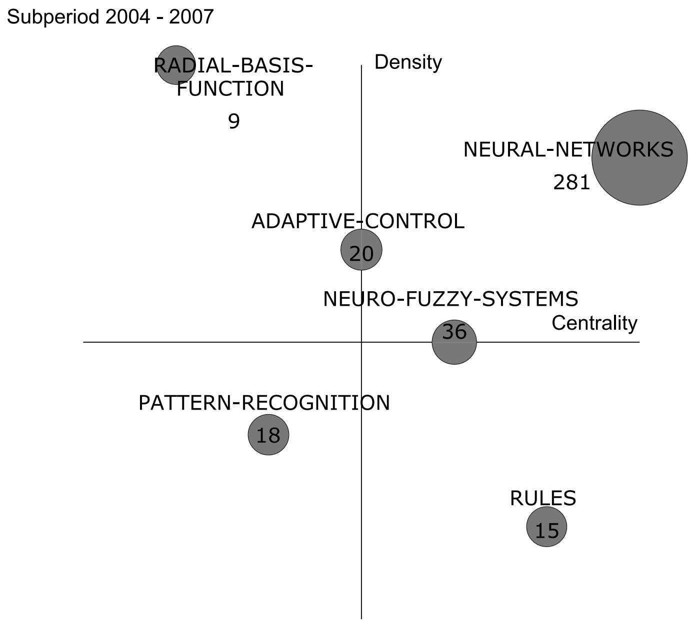


Fig. 8. NNs-FL strategic diagram for the subperiod 2004–2007.

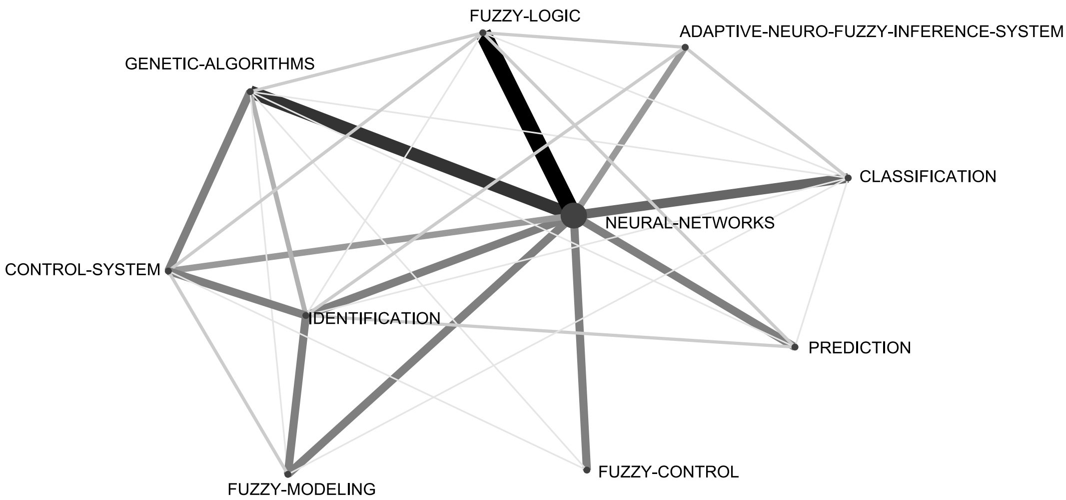


Fig. 9. The *NEURAL-NETWORK* thematic network (subperiod 2004–2007).

the theme *NEURAL-NETWORK* was supposed very conceptually developed, whereas *IDENTIFICATION* (lower-left quadrant) was considered as an incipient discipline, in development process in the NNs-FL based research subfield.

From 2000 to 2003, *NEURAL-NETWORK* (884 papers), *ADAPTIVE-RESONANCE-THEORY* (53 papers), *EXPERT-SYSTEMS* (49 papers), and *RULE-GENERATION* (48 papers) were the four most active themes in this subperiod (see Fig. 7b).

In the last four years (2004–2007), *NEURAL-NETWORK* (281 papers), *NEURO-FUZZY-SYSTEMS* (36 papers) and *ADAPTIVE-CONTROL* (20 papers) were the three most studied themes (see Fig. 8). *NEURAL-NETWORK* was the most developed theme (upper-right quadrant).

Figures 9 and 10 show the *NEURAL-NETWORK* and *NEURO-FUZZY-SYSTEMS* thematic networks for the last four years (2004–2007). As we saw in Fig. 6 in the whole FL-SC study this theme belong to the same theme (*NEURAL-NETWORK*). In the NNs-FL study, the theme *NEURO-FUZZY-SYSTEMS* got the

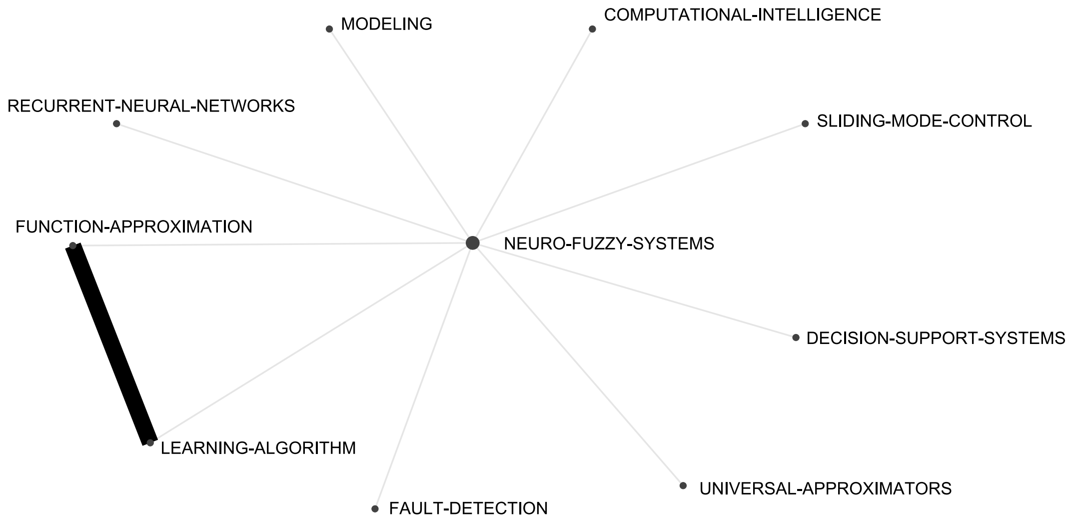


Fig. 10. The *NEURO-FUZZY-SYSTEMS* thematic network (subperiod 2004–2007).

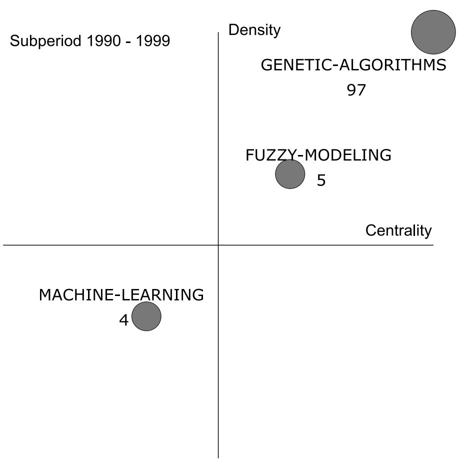


Fig. 11. EAs-FL strategic diagram for the subperiod 1990–1999.

more strong, due to the theme made up its own theme.

3.3. *Analyzing the hybridization between the evolutionary algorithms and the fuzzy fields*

From ISIWoS database [9] 1595 papers on Evolutionary Algorithms and Fuzzy (EAs-FL) hybrid intelligent systems were downloaded. *GENETIC-ALGORITHMS*, with 97 papers, was the most studied theme from 1990 to 1999 (see Fig. 11).

In the second studied subperiod (2000–2003), *GENETIC-ALGORITHMS* (448 papers), *MEMBERSHIP-FUNCTIONS* (30 papers), and *IDENTIFICATION* (30 papers) were the three most studied themes (see Fig. 12a).

Figure 12b shows the most studied themes for the years 2004 to 2007. We can see as *GENETIC-ALGORITHMS*, with 183 papers, was the most active theme again.

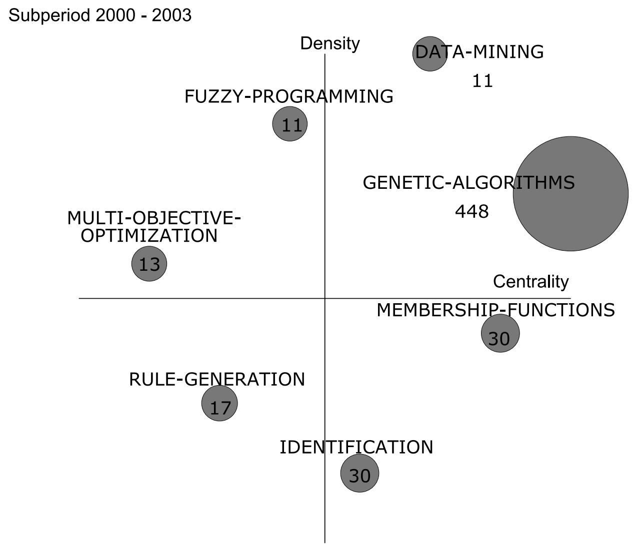
In Figs 13 and 14 the thematic networks for the themes *MEMBERSHIP-FUNCTIONS* (2000–2003) and *RULES* (2004–2007) are shown, respectively.

Figure 13 allows us to study which topics were related with the theme *MEMBERSHIP-FUNCTIONS*. As we can see, there exists strong relations amoung the topics *INDUCTION*, *TRAINING-EXAMPLES* and *KNOWLEDGE-ACQUISITION*. Other important topics related with *MEMBERSHIP-FUNCTIONS* were: *DECISION-MAKING* and *PATTERN-CLASSIFICATION*.

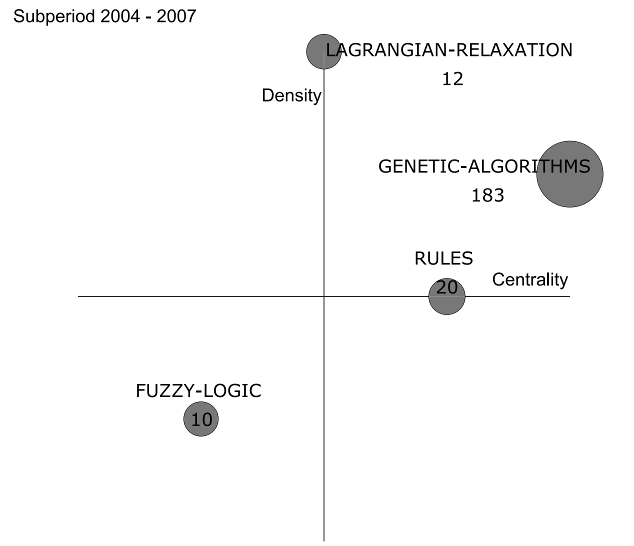
In Fig. 14 we can observe how the theme *RULES* was applied, in the last subperiod, to problems like classification and prediction of times series. Indeed, there exists strong relation with the topic *INFERENCE-SYSTEMS*.

From Figs 11 and 12 we can conclude *GENETIC-ALGORITHMS* seems the most suitable *Evolutionary Algorithm* paradigm to be hybridized with the Fuzzy field. It has grouped 728 papers, almost 46% of published papers in the EAs-FL based research subfield.

In Fig. 15 the thematic network of the theme *GENETIC-ALGORITHMS* for the period 2004–2007 is presented. As we can see in Figs 6 and 9 there exist a strong connection between the topics *NEURAL-NETWORK* and *NEURO-FUZZY-SYSTEMS*.



(a) Period 2000-2003.



(b) Period 2004-2007.

Fig. 12. EAs-FL strategic diagrams for the subperiods 2000–2003 and 2004–2007.

3.4. Analyzing the Hybridization between the Swarm Intelligence and the Fuzzy fields

Because *Swarm Intelligence* is a novel research field,[5] with just 101 original papers treating some aspects of hybrid Swarm Intelligence-Fuzzy (Swarm-FL) intelligent systems, there are not enough data to be analyzed using the same methodology as in above subsections. For analyzing this subfield a global period (1990–2007) has been used.

The main (and unique) detected theme by CoPalRed [5] has been *PARTICLE-SWARM-OPTIMIZATION* (34 papers) whose thematic network is shown in Fig. 16. It can be seen in that network how the research on the Swarm-FL subfield is supported by the other subfields. It is notable the contribution of *Genetic Algorithms* (see the thick link between *GENETIC-ALGORITHMS* and *PARTICLE-SWARM-OPTIMIZATION*).

[5]In ISIWoS [9] there only exist 990 original papers on *Swarm Intelligence* (it was checked using a query combining terms in Table 1 on 1th October 2008).

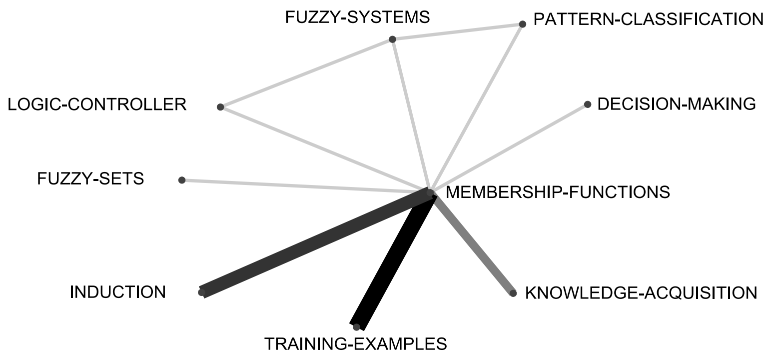


Fig. 13. The *MEMBERSHIP-FUNCTIONS* thematic network (subperiod 2000–2003).

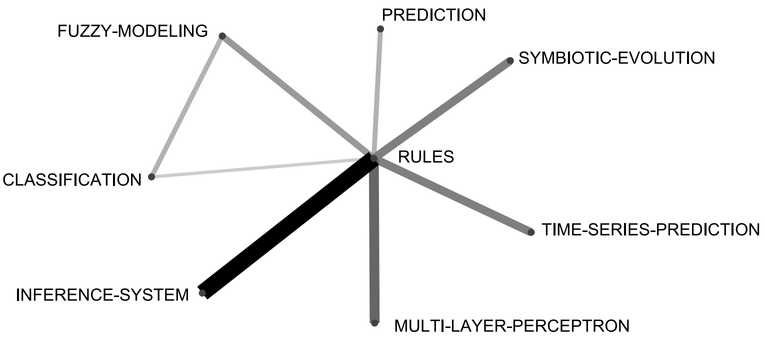


Fig. 14. The *RULES* thematic network (subperiod 2004–2007).

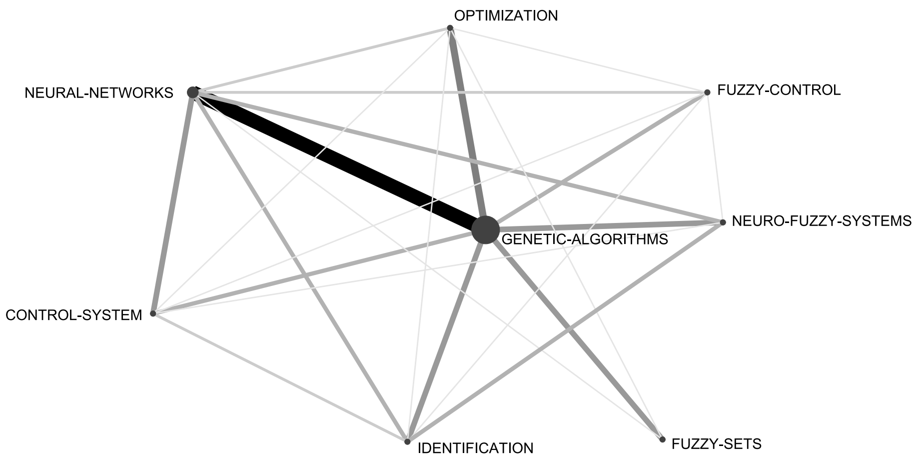


Fig. 15. The *GENETIC-ALGORITHMS* thematic network (subperiod 2004–2007).

Table 2
The 25 most active journals in the FL-SC field (Period 1990–2007)

SOURCE TITLE	RECORD COUNT	%
FUZZY SETS AND SYSTEMS	363	7.05%
IEEE TRANSACTIONS ON FUZZY SYSTEMS	206	4.00%
IEEE TRANSACTIONS ON SYSTEMS MAN AND CYBERNETICS PART B-CYBERNETICS	145	2.82%
IEEE TRANSACTIONS ON NEURAL NETWORKS	129	2.55%
ENGINEERING APPLICATIONS OF ARTIFICIAL INTELLIGENCE	111	2.16%
INFORMATION SCIENCES	90	1.75%
IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS	74	1.44%
EXPERT SYSTEMS WITH APPLICATIONS	69	1.34%
ELECTRIC POWER SYSTEMS RESEARCH	59	1.15%
INTERNATIONAL JOURNAL OF INTELLIGENT SYSTEMS	59	1.15%
JOURNAL OF INTELLIGENT & FUZZY SYSTEMS	58	1.13%
NEUROCOMPUTING	58	1.13%
NEURAL NETWORKS	57	1.11%
IEEE TRANSACTIONS ON POWER SYSTEMS	51	1.00%
INTERNATIONAL JOURNAL OF ADVANCED MANUFACTURING TECHNOLOGY	50	0.98%
NEURAL COMPUTING & APPLICATIONS	50	0.97%
SOFT COMPUTING	49	0.95%
APPLIED SOFT COMPUTING	48	0.93%
EUROPEAN JOURNAL OF OPERATIONAL RESEARCH	47	0.91%
INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH	45	0.87%
PATTERN RECOGNITION	42	0.82%
INTERNATIONAL JOURNAL OF APPROXIMATE REASONING	41	0.80%
INTERNATIONAL JOURNAL OF SYSTEMS SCIENCE	40	0.78%
JOURNAL OF INTELLIGENT & ROBOTIC SYSTEMS	40	0.78%
IEEE TRANSACTIONS ON SYSTEMS MAN AND CYBERNETICS PART C-APPLICATIONS AND REVIEWS	39	0.76%

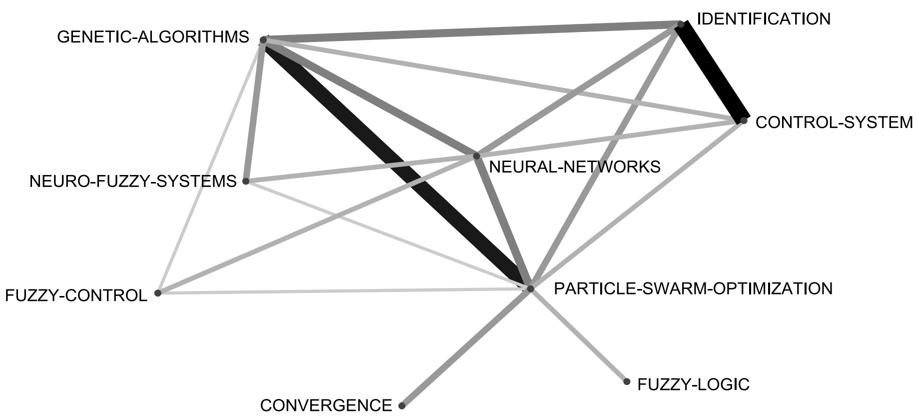


Fig. 16. The *PARTICLE-SWARM-OPTIMIZATION* thematic network.

4. Other related data

In this section, other related data are summarized.

From 1990 to 2007, the most active journals and subject categories working on the FL-SC field are shown in Tables 2 and 3 respectively. In it, we can see as *FUZZY SETS AND SYSTEMS* (363 papers), *IEEE TRANS. ON FUZZY SYSTEMS* (206 papers), *IEEE TRANS. ON SYSTEMS, MAN AND CYBERNETICS, PART B* (145 papers) and *IEEE TRANS. ON NEURAL NETWORKS* (129 papers) are the four journals collecting more published research papers treating some aspects of hybrid intelligent systems. These four journals grouped 843 papers, more than the 16% of those published in the FL-SC field in those years.

With respect to subject categories, the research on FL-SC field has been mainly supported by *Engineering* and *Computer Science* journals. It is also notable the interest of journals of “NATURAL SCIENCES”

Table 3
The 25 most active subject categories in the FL-SC field (Period 1990–2007)

SUBJECT CATEGORY	RECORD COUNT	%
COMPUTER SCIENCE, ARTIFICIAL INTELLIGENCE	1722	33.44%
ENGINEERING, ELECTRICAL & ELECTRONIC	1545	30.00%
AUTOMATION & CONTROL SYSTEMS	704	13.67%
COMPUTER SCIENCE, THEORY & METHODS	670	13.01%
COMPUTER SCIENCE, INTERDISCIPLINARY APPLICATIONS	480	9.32%
MATHEMATICS, APPLIED	465	9.03%
STATISTICS & PROBABILITY	386	7.50%
COMPUTER SCIENCE, CYBERNETICS	276	5.36%
OPERATIONS RESEARCH & MANAGEMENT SCIENCE	273	5.30%
ENGINEERING, MANUFACTURING	259	5.03%
INSTRUMENTS & INSTRUMENTATION	236	4.58%
ENGINEERING, MULTIDISCIPLINARY	233	4.52%
COMPUTER SCIENCE, INFORMATION SYSTEMS	229	4.45%
COMPUTER SCIENCE, HARDWARE & ARCHITECTURE	192	3.73%
ENGINEERING, MECHANICAL	173	3.36%
ENGINEERING, CIVIL	164	3.18%
ENGINEERING, INDUSTRIAL	155	3.01%
COMPUTER SCIENCE, SOFTWARE ENGINEERING	118	2.29%
ENGINEERING, CHEMICAL	118	2.29%
WATER RESOURCES	108	2.10%
ENGINEERING, BIOMEDICAL	103	2.00%
ROBOTICS	96	1.86%
TELECOMMUNICATIONS	78	1.51%
MEDICAL INFORMATICS	73	1.42%
GEOSCIENCES, MULTIDISCIPLINARY	72	1.40%

Table 4
The 25 most active journals in the FL-SC field (Period 2004–2007)

SOURCE TITLE	RECORD COUNT	%
FUZZY SETS AND SYSTEMS	93	4.68%
IEEE TRANSACTIONS ON FUZZY SYSTEMS	57	2.87%
IEEE TRANSACTIONS ON SYSTEMS MAN AND CYBERNETICS PART B-CYBERNETICS	57	2.87%
ENGINEERING APPLICATIONS OF ARTIFICIAL INTELLIGENCE	51	2.57%
EXPERT SYSTEMS WITH APPLICATIONS	46	2.31%
IEEE TRANSACTIONS ON NEURAL NETWORKS	39	1.96%
INFORMATION SCIENCES	38	1.91%
SOFT COMPUTING	38	1.91%
APPLIED SOFT COMPUTING	36	1.81%
IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS	30	1.51%
IEEE TRANSACTIONS ON POWER SYSTEMS	26	1.31%
ELECTRIC POWER SYSTEMS RESEARCH	24	1.21%
INTERNATIONAL JOURNAL OF ADVANCED MANUFACTURING TECHNOLOGY	24	1.21%
NEUROCOMPUTING	23	1.16%
EUROPEAN JOURNAL OF OPERATIONAL RESEARCH	22	1.11%
NEURAL COMPUTING & APPLICATIONS	22	1.11%
JOURNAL OF INTELLIGENT & FUZZY SYSTEMS	19	0.96%
APPLIED MATHEMATICS AND COMPUTATION	18	0.91%
INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH	18	0.91%
INTERNATIONAL JOURNAL OF CONTROL AUTOMATION AND SYSTEMS	16	0.80%
ELECTRIC POWER COMPONENTS AND SYSTEMS	14	0.70%
IEEE TRANSACTIONS ON POWER DELIVERY	14	0.70%
JOURNAL OF HYDROLOGY	14	0.70%
PATTERN RECOGNITION	14	0.70%
IEEE TRANSACTIONS ON SYSTEMS MAN AND CYBERNETICS PART C-APPLICATIONS AND REVIEWS	13	0.65%

Table 5
The 25 most active subject categories in the FL-SC field (Period 2004–2007)

Subject Category	Record Count	%
COMPUTER SCIENCE, ARTIFICIAL INTELLIGENCE	634	31.89%
ENGINEERING, ELECTRICAL & ELECTRONIC	569	28.62%
AUTOMATION & CONTROL SYSTEMS	273	13.73%
COMPUTER SCIENCE, INTERDISCIPLINARY APPLICATIONS	223	11.22%
COMPUTER SCIENCE, THEORY & METHODS	199	10.01%
MATHEMATICS, APPLIED	145	7.29%
OPERATIONS RESEARCH & MANAGEMENT SCIENCE	126	6.34%
STATISTICS & PROBABILITY	105	5.28%
ENGINEERING, MULTIDISCIPLINARY	104	5.23%
COMPUTER SCIENCE, CYBERNETICS	102	5.13%
ENGINEERING, MANUFACTURING	96	4.83%
ENGINEERING, CIVIL	92	4.63%
INSTRUMENTS & INSTRUMENTATION	90	4.53%
COMPUTER SCIENCE, INFORMATION SYSTEMS	88	4.43%
WATER RESOURCES	78	3.92%
ENGINEERING, MECHANICAL	65	3.27%
ENGINEERING, INDUSTRIAL	61	3.07%
COMPUTER SCIENCE, HARDWARE & ARCHITECTURE	55	2.77%
GEOSCIENCES, MULTIDISCIPLINARY	43	2.16%
COMPUTER SCIENCE, SOFTWARE ENGINEERING	42	2.11%
ENGINEERING, BIOMEDICAL	42	2.11%
MATERIALS SCIENCE, MULTIDISCIPLINARY	39	1.96%
ENGINEERING, CHEMICAL	34	1.71%
ENVIRONMENTAL SCIENCES	34	1.71%
TELECOMMUNICATIONS	33	1.66%

in collecting papers applying hybrid intelligent systems on topics related with *Medicine*, *Water Resources*, *Chemist*, *Geosciences*, etc.

Similar data can be shown for the last four years (2004–2007) (See Tables 4 and 5). Table 4 shows as the journals *FUZZY SETS AND SYSTEMS* (93 papers), *IEEE TRANS. ON FUZZY SYSTEMS* (57 papers), *IEEE TRANS. ON SYSTEMS, MAN AND CYBERNETICS, PART B* (145 papers) and *ENGINEERING APPLICATIONS OF ARTIFICIAL INTELLIGENCE* (51 papers) grouped 258 papers (12% of the published papers). Comparing Tables 2 and 4 we can see how the number of published papers is more distributed among the different journals working on the topic.

With respect to subject categories, we can see in Table 5 how the research on FL-SC in the last subperiod (2004–2007) has been mainly supported by journals of *Engineering* and *Computer Science* again. In view of the figures in this table, it can be remarked the increasing interest of "APPLIED" subject categories on using hybrid intelligent systems. Subject categories as those shown in bold-type style in Table 5.

5. Conclusions

In this paper, we have presented a bibliometric study of the FL-SC field. More than 5200 FL-SC research papers on hybrid intelligent systems have been processed. Based on our analysis, we have drawn the visual structure of the FL-SC field.

We have been able to observe how the more important themes have evolved. The hybrid subfields NNs-FL, EAs-FL and Swarm-FL have also been analyzed. In addition, the most active journals and subject categories have been shown.

Acknowledgments

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