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A Bibliometric Overview and Visualization of *Fuzzy Sets and Systems* between 2000 and 2018

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ABSTRACT

Fuzzy Sets and Systems (*FSS*) is an influential international journal of fuzzy research. This study provides a bibliometric overview of the publications of *FSS* from 2000 to 2018. The changes that occurred in the inner structure of this journal are captured by analyzing the bibliometric indicators of 4,348 publications published therein during the period under study. The time profile of this journal is outlined in terms of the number of publications, citations, h-index, category normalized citation impact (CNCI), and g-index. In addition, the most productive and influential authors, institutions, and countries are identified and analyzed. We visualize and illustrate the cocitations network of authors and links of *FSS* with other journals by estimating structural indicators using VOSviewer software. The emerging trends in themes of *FSS* are identified by detecting bursting keywords employing CiteSpace software. It is shown that *FSS* has strong bidirectional connections with other leading journals of fuzzy research. Over 95% of all documents published in *FSS* have been cited at least once. The annual values of the CNCI of the works published in *FSS* are found above unity. Regarding thematic diversity, the social and management sciences research constituted a large share in the documents citing articles published in *FSS*. The average citations were relatively higher for documents published under green Open Access mode in comparison to the paywall set. The results of the study are useful for understanding the knowledge domains of this journal and promising directions for future research in this field.

KEYWORDS

InCites; CNCI; g-index; SNIP; burst detection; CiteSpace; fractional counting method

Introduction

Fuzzy Sets and Systems (*FSS*) is one of the most influential international journals focused on advanced research connected to fuzzy sets theory and application.[1] According to its first editorial perspective, Lotfi A. Zadeh, the father of mathematical fuzzy logic, together with Hans J. Zimmermann and Constantin V. Negoita, launched this journal in 1978. At that time, it was the first international journal exclusively focused on development in theory and applications of fuzzy mathematics. Initially, *FSS* published one volume with four issues per annum. In the first year of its foundation, *FSS* published 23 documents. Now, the journal has made enormous contributions to the scientific literature with the publication of 8,398 documents. With the rapid development in the field of information representation and management, this journal grew very fast. During the first two years of its foundation, it published one volume per year containing four issues per volume. Between 1980 and 1982, 1983 and 1986, 1987 and 1988, 1989 and 1990, and 1991 and 1992, *FSS* published two, three, four, five, and six volumes per year, respectively, with three issues per volume. The number of volumes published jumped to eight per year in 1992. From 2006 to 2010, *FSS* published one volume per year, containing 24 issues. Since 2007, *FSS* has started to publish

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theme-based volumes. Since 2011, the journal has been publishing 24 volumes per year, with one issue per volume. At present, the journal encompasses broad-spectrum fields of fuzzy research, ranging from fuzzy logic, fuzzy sets, fuzzy system, fuzzy control, fuzzy numbers, linguistic variable, fuzzy decision, and information granulation to generalization of information measures, principles, and technologies. In this process, *FSS* publishes high-quality research conducted by scholars of different disciplines, including mathematics, statistics, medical sciences, linguistics, management sciences, social sciences, economics, engineering, and computer science. It plays an important role in the dissemination of knowledge pertaining to the advancement of fuzzy sets and their applications for solving real-world problems. The impact factor (IF; a proxy of influence) of this journal has grown steadily, increasing from 0.364 in 1990 to 2.907 in 2019. Likewise, the value of its CiteScore increased from 5.1 in 2011 to 6.5 in 2019. *FSS* has enjoyed a SCImago Journal Rank (SJR) of 1.062 and a Source Normalized Impact per Paper (SNIP) of 2.035 for the year 2019. The rising trend seen in standard indicators of the impact of *FSS* provides a sufficient clue to librarians for the inclusion of this journal in their subscription list. This increase may partially be attributable to growth in size and visibility of the overall fuzzy research corpus. Indeed, *FSS* is a recognized outlet for good-quality fuzzy research. The papers published in this journal are indexed in well-known standard databases, namely Web of Science, Scopus, and Science Citation Index.

Currently, the studies identifying foremost trends occurring in the inner structure pattern and the influence landscape of a particular journal have received a considerable amount of attention. Motivated by this development, the current study aims to provide an overview of emerging trends in the bibliometric profile of *FSS*. In so doing, it outlines the foremost trends measured in terms of bibliometric indicators of documents published in *FSS* from 2000 to 2018. To achieve this aim, the study is intended to answer the following intriguing research questions (RQ):

RQ1: What is the current state of a bibliometric profile of *FSS*?
RQ2: How is *FSS* currently linked to other journals?
RQ3: What are the leading thematic trends in *FSS*?
RQ4: What are the growth prospects of *FSS*?

The findings, strategies, and methods employed in the current study will be potentially useful for editors, librarians, practitioners, scholars, and others interested in the bibliographic analysis of a journal. The study is helpful for academic librarian readers in suggesting relevant research material to library users in the field of disciplines where fuzzy sets and systems play a significant role, notably social and management sciences. For specialty-focused librarians, the analysis is useful to track journal performance and make a scientific decision on the subscription of the journal studied. It may also serve as a training resource for librarians.

Rationale for the study

Bibliometrics is a research field of library science. A bibliometric study of a leading journal of a research field shows the evolution and present state of knowledge. It influences future studies in that field and the research lifecycle. Bibliometric analysis is a useful mathematical procedure for the evaluation of a journal's development and improvement of its strategy. Such analysis facilitates outlining the profile of a journal by exploring the structure and scholarly trend evolved in that journal. By so doing, such studies reveal a broad picture and in-depth analysis of the inner structure pattern of a journal. The findings from such analyses are of importance to scholars, practitioners, librarians, publishers, and editors interested in the journal. In this process, these studies help editors in understanding the growth prospects of that journal. The results of such studies also prioritize the choice of librarians in subscription of journals.

Nowadays, the fuzzy sets theory has found wide applications in modeling and solving real-world problems.[2] In essence, visualization and exploration of the areas of growing research focus on the fuzzy sciences and their knowledge domain uphold further development in this field. A few extant

studies have attempted to provide an account of the progress in knowledge domains of fuzzy research.[3] One strand of this literature is based on area-specific research while another focuses on the exploration of documents published in a particular journal of the fuzzy field.[4]

In order to highlight the rising importance of journal-specific bibliometric analysis, a bibliometric overview of relevant literature in the area of fuzzy research is given in Table 1. The information in Table 1 includes authors of journal-specific studies, title of a journal, IF, duration studied, bibliometric indices employed, number of publications covered, and number of citations received by these studies in the documents indexed in the Web of Science database.[5] The values of IF and SNIP of journals reported in Table 1 indicate that these are influential. A glance at Column 7 of Table 1 makes it clear that bibliometric analyses of leading journals are getting wide scholarly attention. For instance, in 2017, Yu et al.[6] applied bibliometric techniques, using CiteSpace, to analyze the salient pattern and emerging trends that evolved in scholarly works published in *Information Sciences* from 1987 to 2016. It was found that the most cited themes of this journal were fuzzy sets and rough sets followed by decision making and information fusion. Merigó et al.[7] employed VOSviewer to develop networks of cocitations and bibliographic coupling of publications that appeared in *International Journal of Intelligent Systems* over the period 1986–2015. Likewise, Yu et al.[8] investigated the structure of *Fuzzy Optimization and Decision Making* (*FODM*) and detected bursting keywords that occurred in its publications published from 2002 to 2017. Laengle et al.[9] examined prolific scholars, their affiliations, and the citation structure of documents published in *FSS* between 1978 and 2016. They reported that *FSS* is a preferred venue in the field of computer science and applied mathematics, mainly for the scholars having affiliating institutions of Europe, North America, and East Asia.

To the best of our knowledge, there is a lack of a detailed and in-depth study providing the analysis of the impact of the research published in this journal on the related scholarly work assessed by employing standard bibliometric indices, including Category Normalized Citation Impact (CNCI), SNIP, SJR, CiteScore, and g-index. Likewise, the analysis of Open Access (OA) documents and citing disciplines can provide the beneficial impetus for librarians, editors, and publishers. The present study attempts to fill these important gaps in the scientific literature.

Table 1. Recent Bibliometric Studies of Select Journals of Fuzzy Sciences

Authors	Journal	IF	SNIP	Duration Covered	NPS	Methods	TC
Zhang et al.[13]	*Knowledge-Based Systems*	5.101	2.902	1991–2016	2657	h, TP, TC, CP, CY, CN, CON	16
Yu et al.[14]	*IEEE Transactions on Fuzzy Systems*	8.759	3.206	1994–2015	1904	h, TP, TC, CP, CN, CAN, BC	26
Merigó et al.[15]	*Information Sciences*	5.524	2.688	1968–2016	7,847	h, TP, TC, CP, CY, CN, BC, CON	30
Wang et al.[16]	*International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems*	1.882	0.646	1993–2016	1,135	h, TP, TC, CP, CY, CN, CON, BC	22
Tang et al.[17]	*International Journal of Fuzzy Systems*	3.085	1.436	2007–2017	895	h, TP, TC, CP, CN	8
Muhuri et al.[18]	*Applied Soft Computing*	4.873	2.520	2004–2016	3,680	h, TP, TC, CP, CY, CN, BC	9
Laengle et al.[19]	*Group Decision and Negotiation*	2.010	0.939	1992–2016	863	h, TP, TC, CP, CY, CN, BC, CON	7
Yu et al.[20]	*Applied Intelligence*	2.882	1.571	1993–2018	1,451	h, TP, TC, CP, CY, CN, BC, BD	8
Merigó et al.[21]	*Soft Computing*	2.784	1.593	1997–2016	2,331	h, TP, TC, CP, CY, CN, BC, CON	3

IF = Impact Factor taken from 2019 edition of Journal Citation Report published by Clarivate Analytics, NPS = No. of publications studied, h = h-index, TP = Total publications, TC = Total citations, CP = Citations per publication, CY = Citations per year, CN = Cocitation network, CON = Cooccurrence network, BD = Burst detection, CAN = Coauthorship network, and BC = Bibliographic coupling. Source Normalized Impact per Paper (SNIP) is taken for the year 2019.

Methods of analysis

Regarding the use of methods of analysis, the present analysis builds on extant bibliometric studies.[10] It is based on a forward-looking approach. It captures the recent changes that occurred in *FSS* from a macroperspective.[11] To do so, it covers publications published in this journal from 2000 to 2018. The Web of Science is one of the most widely used databases in bibliometric studies. The data used in the study were primarily taken from the Web of Science core collection database on November 10, 2019. The IF is a useful indicator of the performance of a journal. However, journal metrics like IF do not give an adequate and comparative assessment of a journal. A basket of relevant metrics can offer an avenue to an informed and more meaningful journal performance evaluation for wider comparisons and contextualization.[12] In order to provide a variety of perspectives, we also employ several other standard indicators so that each reader can understand the results based on their specific interests and priorities. Our choice of use of the Web of Science database is supported by the fact that it provides the InCites platform of Clarivate Analytics. The InCites platform gives useful information for analysis of the impact of documents published under different access modes, percentage of documents cited, IF, and CNCI.

The impact analysis conducted using Web of Science metrics is supplemented by employing Scopus database-based indices, namely SNIP, SJR, and CiteScore. The study took place over a time span of 19 recent complete calendar years, 2000 to 2018. Regarding search strategy, we began by selecting the option of "publication titles" and introduced the keywords "Fuzzy Sets and Systems" in the Web of Science search engine. Thereafter, the InCites option was used to obtain information on CNCI. For further analysis, the data were downloaded using the export option. The analysis includes all types of publications of *FSS*, as all of these have been cited widely in the relevant literature. It examines the development trends seen in recent years in the context of leading authors, publications, countries, and institutions of this journal.

The productivity is measured in terms of the number of publications while influence is computed by counting the number of citations. In order to have a robust analysis, other performance indicators, namely h-index, g-index, CNCI, percentage of documents cited, citations per publication, and citations per year supplement these indices. The emerging trends in the knowledge domain are identified through the construction of networks and detection of bursting keywords. The h-index was calculated by arranging the publications in descending order of the number of their citations. The highest number of publications of that received h or more citations each is defined as the h-index. The g-index is an improvement over the h-index to the extent that it also considers the citation count of very highly cited papers. Drawing on Wang et al.,[22] we employ the information visualization technologies of the latest versions of VOSviewer[23] for the construction of network maps, and CiteSpace[24] software for temporal evaluation of bursting keywords. These standard methods of bibliometric analysis used in this study have been recommended by existing studies of a similar nature. Our choice of these freely available and easily operational bibliometric software packages is also supported by the fact that VOSviewer has better visualization ability. However, CiteSpace pays more attention to temporal analysis. The results of the study are useful to the scholars and practitioners of fuzzy sets theory and applications for knowing information about the most significant bibliometric aspects of the recent research published in *FSS*.

This study is organized into six sections. The second section presents the basic statistical analysis of publications, citation structure, leading authors, institutions, countries, documents published, and most cited authors, works, and sources in *FSS*. The third section constructs and illustrates cocitation networks of authors, sources, and references cocited in this journal. A snapshot of the cooccurrence of keywords is developed employing VOSviewer software and the bursting keywords are detected employing CiteSpace software in the fourth section. The fifth section discusses the implications of the results of this study for the growth prospects of *FSS*. The sixth section summarizes the main findings of this study and provides concluding remarks.

Statistical characteristics of works published in *FSS*

We begin by analyzing the annual statistical characteristics of 4,348 recent works published in *FSS* from 2000 to 2018. On the date of retrieving data from Web of Science, these publications were cited 111,867 times with an h-index of 125. Each of these works was cited an average of 25.73 times.

Temporal behaviour of documents published in FSS

Figure 1 exhibits the temporal profile of *FSS* measured in terms of number of yearly publications and their h-index over the period 2000 to 2018. A glance at Figure 1 makes it clear that every year *FSS* publishes a relatively large number of documents. The number of publications published in *FSS* has fluctuated over the years. In fact, the number of works published in *FSS* reached its peak of 348 in 2001. From 2002 to 2009, it varied between 252 and 236. Since 2010, it happened to fall. However, after taking a dip to 178 documents in 2011, it again started to grow, reaching 256 in 2016. After going down to 189 publications in 2017, it again showed signs of recovery during the last year under analysis with the publication of 193 documents. On average, *FSS* published 229 documents every year during the period being analyzed.

The annual number of publications of *FSS* exhibited a declining trend during this period. However, a comparison of the numbers of documents published in *FSS* with another mainstream journal of the fuzzy field, *FODM*, indicates that this number of total publications of *FSS* is at least seven times higher than that of *FODM*. It is worth noting that the total number of works published in *FSS* during the period under analysis is almost double that of another reputable international journal of the same field, *IEEE Transactions on Fuzzy Systems*. Likewise, a new Web of Science–indexed international journal of the fuzzy set community, titled *International Journal of Fuzzy Systems*, published only 152 documents in 2017. Another related international journal rated in terms of relatively high IF (7.229), *International Journal of Intelligent Systems*, publishes on average 60 papers per annum.

The h-index of the annual publications of this journal is relatively good, with a value of more than 20 except for the latest two years. It indicates that, every year, 20 such publications have been published in *FSS* that have each been cited at least 20 times in the documents indexed in the Web of Science database. A cursory look at Figure 1 makes it clear that the volume of documents published in *FSS* and the value of their h-index are associated with each other, with a correlation coefficient of 0.666. A medium value of the h-index in the most recent years may be due to the fact that these publications have not yet had sufficient time to gain a considerable citation rate.

A comparative analysis of the yearly value of the h-index gained by *FSS* with respect to *FODM* indicates that the h-index of *FSS* is more than twice that of *FODM*. More importantly, *FSS* has been the most cited source for the works published in *FODM* from 2002 to 2017 and for the *International Journal of Intelligent Systems* from 1986 to 2015. In terms of the value of the h-index only within fuzzy

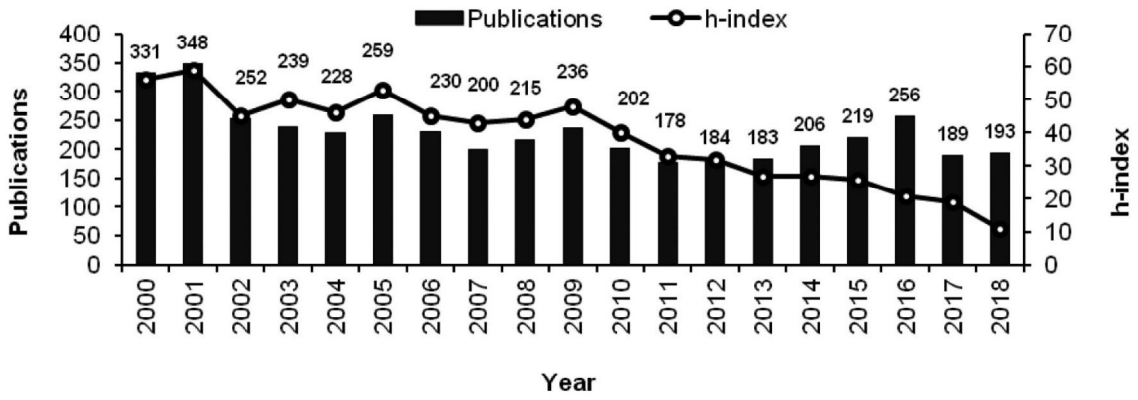

Figure 1. Year wise distribution of publications of *FSS* from 2000 to 2018.

research, *FSS* (h:119) ranked first, *IEEE Transactions on on Fuzzy Systems* (h:97) bagged second position, *IEEE Transactions on Systems, Man, and Cybernetics: Systems* (h:76) enjoyed third place, *Information Sciences* (h: 65) received the fourth position, and *European Journal of Operational Research* (h:58) ranked fifth. Among the 30 most influential journals in the field of fuzzy research, the value of the h-index varied from 21 to 119. Clearly, *FSS* is one of the prominent journals in the fuzzy research field.

Types of documents published in *FSS*

Figure 2 shows the numbers and percentage share of the different types of 4,348 publications from *FSS* covered in this study. Different types of publications were found in the total works published in *FSS*. Articles (4,163), with a share of 95.75%, dominate these documents. They were followed by editorial material (120), which includes research reports and book reviews, accounting for 2.76% of total publications. Other research work types include corrections (26), biographical items (22), reviews (9), letters (6), and bibliographies (2).

Regarding another determinant of citations, during the period under study, out of 4,348 publications, a total of 148 (3.40%) documents were published under OA mode. These comprise 130 (87.84%) articles, 11 proceeding papers, 3 editorial materials, 2 biographical items, and 2 corrections. Out of 148 OA documents, 135 were published under green OA. The citations per item published under the green OA option (31.53) were higher in comparison to those that can be accessed only through subscription (25.53).

Trend in cited documents

Figure 3 displays the annual trend in CNCI estimated using InCites, and percentage of documents cited from 2000 to 2018. As seen in Figure 3, the annual values of CNCI are above unity. It indicates that the impact performance of *FSS* is above the world's average. This finding corroborates our earlier finding that *FSS* is an influential journal. Regarding the highest average quality of documents, 98% of documents published in 2008 have been cited at least once. On average, 95% of all documents published in *FSS* during the period under study were cited at least

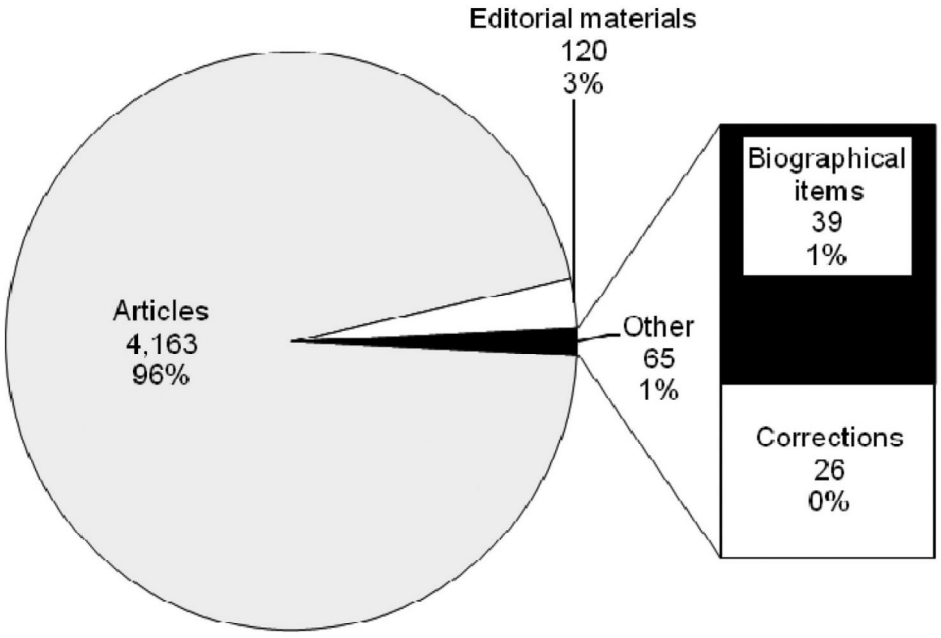

Figure 2. Types of documents published in *FSS* from 2000 to 2018.

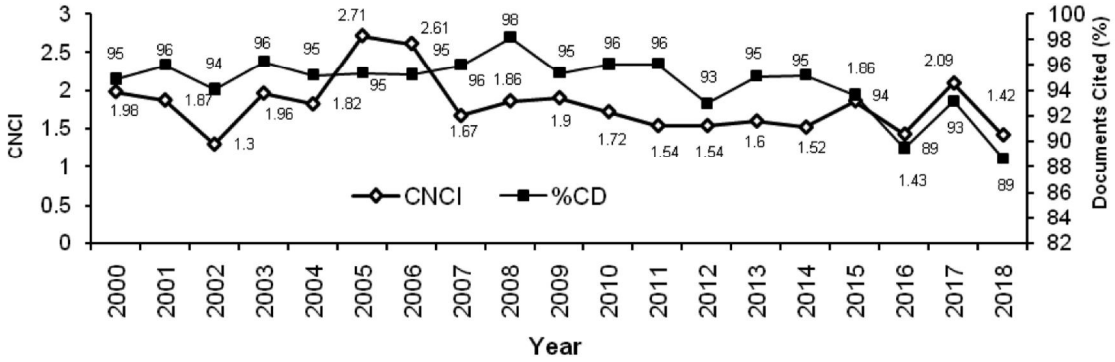

Figure 3. Evolution of category normalized citation impact of *FSS* from 2000 to 2018.

once. These findings indicate a substantial influence and usefulness of *FSS*. This conclusion also corroborates with the aforementioned good IF of the journal. In the context of a comparison of citation trends seen during the 20th (1978–1999) and 21st (2000–2018) centuries, most of the top-cited papers of *FSS* were published during the 20th century. However, *FSS* has maintained its influence in overall fuzzy research.

Most productive authors in *FSS*

During the period under study, 4,693 authors have contributed their research documents to *FSS*. The bibliometric information regarding the 10 most productive authors of *FSS* ranked in terms of the number of publications published is presented in Table 2, including their affiliation, total citations (TC), percentage share in all works published in this journal, citations per publication, and h-index. The top 20 authors together contributed to 14.56% of total works published in *FSS* during the period analyzed. Among the 10 leading authors, each had contributed more than 27 works to *FSS* while the first five authors have published over 30 publications in *FSS*. R. Mesiar from the Slovak University of Technology in Bratislava, Slovakia, ranked first with the publication of 83 works in *FSS* and these documents were cited 1,656 times. The value of the h-index of these documents was 22. B. De Baets from Ghent University, Belgium, follows this author with 50 publications having 1,097 citations. The citations per publication of the second-most-productive author are higher than that of the first rank author, while the reverse is true in the case of the h-index and g-index of their publications. The third top author, W. Pedrycz (all-time second-most-

Table 2. Most Productive Authors of *FSS* from 2000 to 2018

Rank	Author	Institution	Country	TP	TC	TC/TP	h-index	g-index
1	Mesiar, R.	Slovak University of Technology in Bratislava	Slovakia	83	1,656	19.95	22	40
2	De Baets, B.	Ghent University	Belgium	50	1,097	21.94	18	33
3	Pedrycz, W.	University of Alberta	Canada	50	1,844	36.88	24	42
4	Fang, J. X.	Nanjing Normal University	China	36	306	8.5	10	17
5	Torrens, J.	University of the Balearic Islands	Spain	32	791	24.72	17	28
6	Bustince, H.	Public University of Navarra	Spain	31	1,462	47.16	19	31
7	Shi, F. G.	Beijing Institute of Technology	China	29	388	13.38	12	19
8	Wu, C. X.	Harbin Institute of Technology	China	29	570	19.66	13	23
9	Zhang, D. X.	Sichuan University	China	28	397	14.18	10	19
10	Novak, V.	University of Ostrava	Czech Republic	27	825	30.56	17	27

g = g-index. The rest of the abbreviations are the same as in Table 1.

productive author of *FSS*) from the University of Alberta, Canada, leads both the first and second authors in terms of total citations, citations per publication, h-index, and g-index with values of these performance indicators as 1,844, 36.38, 24, and 42, respectively. It is worth mentioning here that this author also tops the whole list in terms of the value of the h-index and g-index.

The publications authored by S. C. Tong from Liaoning University of Technology, China, have gained the highest total citations (2,345) as well as citations per publication (90.19). This most influential author of *FSS* is an associate editor for several leading journals of fuzzy research, namely *IEEE Transactions on Systems, Man and Cybernetics: Systems* (IF: 7.351), *International Journal of Fuzzy Systems* (IF: 3.085), and *Neurocomputing* (IF: 4.072). E. E. Kerre, Ghent University, Belgium, follows this author in terms of the value of average citations.

Each publication of E. E. Kerre is cited an average of 73.29 times. It is interesting to note that out of 20 leading authors of *FSS*, seven authors, namely R. Mesiar, D. Dubois, B. De Baets, W. Pedrycz, C. X. Wu, S. C. Tong, and E. E. Kerre, have already been identified as the most productive and influential authors in the overall field of fuzzy research. Out of the top 20 authors of *FSS*, eight were affiliated with institutions of China and two authors each were from Belgium, Spain, and the Czech Republic.

Most cited documents of *FSS*

FSS has published a series of influential research documents that have a noteworthy scholarly impact in the field of theory and application domains of fuzzy sets. A list of the 10 most cited documents published in *FSS* from 2000 to 2018 is given in Table 3, including their TC, citation per year, title, and year of publication. These top-cited documents have received 10,578 citations that form 9.46% of the total citations gained by all documents under study. The individual citations of these documents vary from 1,485 to 323. All of these documents were published before 2008. More importantly, 15 of these most cited documents were published from 2000 to 2001.

Table 3. Ten Most Cited Works Published in *FSS*

Rank	TC	Title	Author/s	Year	TC/Y
1	1485	"Extensions of the TOPSIS for group decision-making under fuzzy environment"	Chen, C. T.	2000	74.25
2	989	"Linguistic decision analysis: Steps for solving decision problems under linguistic information"	Herrera, F., Herrera-Viedma, E.	2000	49.45
3	699	"Distances between intuitionistic fuzzy sets"	Szmidt, E., Kacprzyk, J.	2000	34.95
4	620	"Monoidal t-norm based logic: Towards a logic for left-continuous t-norms"	Esteva, F., Godo, L.	2001	32.63
5	601	"Multicriteria fuzzy decision-making problems based on vague set theory"	Hong, D. H., Choi, C. H.	2000	30.05
6	500	"A fusion approach for managing multi-granularity linguistic term sets in decision making"	Herrera, F., Herrera-Viedma, E., Martinez, L.	2000	25
7	473	"On the relationship between some extensions of fuzzy set theory"	Deschrijver, G., Kerre, E. E.	2003	27.82
8	461	"Entropy for intuitionistic fuzzy sets"	Szmidt, E., Kacprzyk, J.	2001	24.26
9	459	"Ten years of genetic fuzzy systems: Current framework and new trends"	Cordon, O., Gomide, F., Herrera, F., Hoffmann, F., Magdalena, L	2004	28.69
10	439	"Generalizations of the differentiability of fuzzy-number-valued functions with applications to fuzzy differential equations"	Bede, B., Gal, S. G.	2005	29.27

TC = Total citations, and Y = Years since publication of a document.

Regarding citations per year, each document is cited at least 16 times. These publications include research on theoretical and applied advancement in fuzzy sets theory pertaining to multicriteria decision making, linguistic decision analysis, fuzzy control, fuzzy programming, genetic fuzzy systems, fuzzy transforms, fuzzy numbers, and generalizations of fuzzy information measures. The highly cited article authored by C. T. Chen in 2000 has been cited 1,485 times. This single-authored research paper on the extension of the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method to the fuzzy environment for group decision making tops the list in terms of citations per year (74.25) as well. This research paper secured a position in the top 50 all-time most cited papers in the field of overall fuzzy research. It has also held a position among highly cited papers of fuzzy decision research. The next four documents cited more than 600 times are: Herrera et al. (2000), Szmidt and Kacprzyk (2000), Esteva and Godo (2000), and Hong and Choi (2000). The second one also gets the same rank in terms of citations per year (see Table 3).

Most productive institutions in *FSS*

Now we investigate the most productive institutions. A total of 1,734 institutions have contributed to the *FSS* documents being analyzed. Table 4 lists the 10 leading institutions in *FSS* ranked in terms of the number of publications.

The scholars affiliated with these top-contributing institutions have enjoyed authorship in 19.71% of all works published in *FSS*. This high concentration of a few institutions in *FSS* indicates a large untapped potential for further growth of this journal. Slovak University of Technology Bratislava of Slovakia is the most productive institution, followed closely by Ghent University in Belgium and University of Ostrava in the Czech Republic. It is interesting to note here that Ghent University was ranked 69th by the Academic Ranking of World Universities in 2017. This university also tops our list in terms of the h-index (h: 31). Each of these top three institutions has contributed more than 110 documents to *FSS*. The value of the h-index of each of these institutions is at least 29. Among the top 20 institutions publishing their research works in FSS, 12 institutions (i.e., Slovak University of Technology Bratislava [46th], Ghent University [11th], University of Ostrava [43rd], University of Granada [1st], Czech Academy of Sciences [37th], Polish Academy of Sciences 295 [10th], University of Oviedo [29th], University of Alberta [18th], Harbin Institute of Technology [21st], Public University of Navarra [45th], Northeastern University [34th], and Johannes Kepler University Linz [48th]), have secured positions in 50 most productive institutions contributing to overall all-time fuzzy research. University of Granada (TC/total publications [TP]: 52), and Polish Academy of Sciences (g: 60) top our list in terms of citations per publication, and g-index, respectively.

Table 4. Most Productive Institutions in *FSS*

Rank	Institution	Country	TP	TC	TC/TP	h-index	g-index
1	Slovak University of Technology Bratislava	Slovakia	119	2156	18.12	25	46
2	Ghent University	Belgium	118	3586	30.39	31	59
3	University of Ostrava	Czech Republic	112	3088	27.57	29	55
4	University of Granada	Spain	94	4589	48.82	29	67
5	National Center for Scientific Research	France	87	3231	37.14	27	56
6	Czech Academy of Sciences	Czech Republic	72	1964	27.28	26	44
7	Polish Academy of Sciences	Poland	69	3600	52.17	27	60
8	Shaanxi Normal University	China	63	961	15.25	17	31
9	Nanjing Normal University	China	62	1312	21.16	17	36
10	University of Oviedo	Spain	61	962	15.77	15	31

The abbreviations are the same as in Table 1.

Czech Republic, Spain, and China lead our list of top 10 institutions with two institutions each. Each of the other countries listed here has only one leading institution. It can be seen from the last three columns of Table 4 that the publications published by these leading institutions have received impressive total citations, citations per year, and h-index.

Most productive countries in *FSS*

The authors of documents published in *FSS* are spread throughout the world. *FSS*, as few other influential journals of this field, enjoys geographical distribution of authors in more than 100 countries. Ten leading contributing countries with at least 173 publications in *FSS* are listed in Table 5, including level of economic development, number of publications, total citations, citations per publication, h-index, and g-index.

There exists a large variation in number of publications of even these most productive countries. For instance, China, a developing country, tops the list in terms of number of publications (950), total citations (23,857), h-index (75), and g-index (154). Currently, its major focus is on fuzzy sets, artificial intelligence, fuzzy logic, uninorms, adaptive control systems, lyapunov functions, and fuzzy inference. It may be added here that Chinese authors also enjoy this most productive and influential researchers status for many other leading international journals of this field, like *Information Sciences, Knowledge-Based Systems, Applied Soft Computing, Soft Computing*, and *FODM*. It is followed distantly by Spain, which has contributed to 561 publications in *FSS* with 14,435 total citations, 27.73 citations per publication, an h-index of 55, and a g-index of 120. Spain emphasizes more on fuzzy sets, artificial intelligence, fuzzy logic, aggregation functions, and mathematical operators. The next largest contributor is the United States (306), followed by the Czech Republic (283), Taiwan (281), and Italy (225). It may be added here that the United States was a leading contributor to *FSS* in 1978, 1987, 1989, 1991, 1994, 1996, and 1997. However, since the second half of the 2000s, the United States and Japan have lost their level of contribution to the journal, particularly in favor of Spain and the Czech Republic. The United States focuses more on fuzzy set theory, decision making, and fuzzy numbers. Regarding another developing country, India, which enjoyed the highest contribution in 1992, it has also seen a decline in its share in *FSS* during the last two decades. In the context of U.S.-, India-, and Japan-based scholars, *Applied Soft Computing* and *Soft Computing* may be termed as peers and rivals to *FSS*. Regarding the status of U.S. supremacy in overall fuzzy research, its contribution in similar journals like *Expert Systems with Applications, Knowledge-Based Systems*, and *Journal of Intelligent and Fuzzy Systems* is still substantial. However, the number of publications authored by U.S.-based fuzzy research scholars has not kept pace with that of China. Note that the numbers of citations received by publications of the Czech Republic (TC: 5,744) are far less than that of Taiwan (TC: 11,293). It partially may be because most of the documents from the Czech Republic were recently published in *FSS*. Taiwan, a developed country, also tops the list of top 10 productive countries in the terms of citations per publication (TC/TP: 40.19).

Table 5. Most Productive Countries in *FSS*

Rank	Country	DS	TP	TC	TC/TP	h-index	g-index
1	China	DC	950	23,857	25.11	75	154
2	Spain	DE	561	14,435	27.73	55	120
3	United States	DE	306	9,244	30.21	47	96
4	Czech Republic	DE	283	5,744	20.3	38	75
5	Taiwan	DE	281	11,293	40.19	52	106
6	Italy	DE	225	3,404	15.13	30	58
7	France	DE	196	5,779	29.48	43	76
8	Poland	DE	189	5,802	30.7	39	76
9	Slovakia	DE	185	2,949	15.94	27	54
10	Japan	DE	173	5,062	29.26	42	71

DS = Development status, DC = Developing country, DE = Developed economy. The rest of the abbreviations are the same as in Table 1.

Table 6. Top Sources, Countries, Institutions, and Subjects Citing Works Published in *FSS*.

Rank	Source	TCP	% of TCP	Country	TCP	Institution	TCP	Discipline	TCP
1	*Fuzzy Sets and Systems*	2,911	8.15	China	12,894	Islamic Azad University	889	Computer science	20,791
2	*Information Sciences*	1,653	4.63	Iran	3,280	Northeastern University China	584	Engineering	10,536
3	*Journal of Intelligent Fuzzy Systems*	1,517	4.25	Spain	2,611	University of Granada	521	Mathematics	8,585
4	*IEEE Transactions on Fuzzy Systems*	1,238	3.47	Taiwan	2,523	National Center for Scientific Research	460	Automation control systems	3,810
5	*Expert Systems with Applications*	1,018	2.85	United States	2,217	Sichuan University	441	Operations research management science	3,269
6	*Applied Soft Computing*	871	2.44	India	2,071	Harbin Institute of Technology	437	Science, technology, other topics	1,361
7	*Soft Computing*	835	2.34	Turkey	1,512	University of Tehran	435	Business economics	1,201
8	*Neurocomputing*	605	1.69	Canada	1,392	Southeast University China	429	Environmental sciences, ecology	983
9	*International Journal of Approximate Reasoning*	528	1.48	South Korea	1,269	Polish Academy of Sciences	417	Instruments, instrumentation	885
10	*International Journal of Fuzzy Systems*	461	1.29	England	1,256	Indian Institute of Technology System	411	Mechanics	773

TCP = Total citing publications.

Who pays attention to *FSS*

We now identify the origin of the citations of *FSS*. *FSS* is a highly globalized journal in the field of mathematics and computer science. The audience and contributors of *FSS* are distributed across the globe. The publications published in *FSS* are cited in a wide range of documents. The scholarly attention gained by *FSS* is analyzed in terms of four aspects—namely, source, country, institution, and subject—citing the documents published in this journal. Detailed information regarding these aspects is presented in Table 6. The top 10 sources listed in Table 6 account for 32.59% of all documents indexed in the Web of Science Core Collection citing publications published in *FSS*. In terms of citing sources, *FSS* itself is ranked first, with 2,911 documents or 8.15% of all citing documents. This pattern of the highest share of self-citations of *FSS* is similar to several other leading journals of fuzzy sciences; namely, *Information Sciences, Applied Soft Computing*, and *Soft Computing*. It implies that the documents published in *FSS* have shaped the future research work published in this journal. In second place appears *Information Sciences* with 1,653 documents citing publications of *FSS*. The *Journal of Intelligent Fuzzy Systems* (1,517), *IEEE Transactions on Fuzzy Systems* (1,238), and *Expert Systems with Applications* (1,018), respectively, follow it closely.

Regarding country, Chinese researchers cite most of the *FSS* publications. China has also enjoyed this status of the top-citing country in the case of documents published in other similar journals: *Information Sciences* and *FODM*. This finding is supported by the fact that China is the most productive country in respect to all-time overall fuzzy research. In second place appears Iran, with 3,280 works citing *FSS* publications. The other countries have less than 3,000 publications that cite *FSS* documents. As such, Spain (2,611), Taiwan (2,523), the United States (2,217), and India (2,071) are ranked in third to sixth positions, respectively. Turkey, Canada, South Korea, and England complete the leading 10 of this ranking list.

It can be seen from Table 6 that Islamic Azad University from Iran (a developing country) tops the list in terms of institutions citing documents published in *FSS*, with 889 publications. The scholars of Northeastern University China have authorship in 584 publications that cite *FSS* works and this university is ranked second. Likewise, University of Granada and the National Center for Scientific Research of France occupy third and fourth positions, with 521 and 460 such documents, respectively. It may be added here that scholars from developing countries have paid considerable attention to research published in *FSS*.

On the discipline side, the documents published in *FSS* have contributed to a far-reaching shift in almost all fields of science to allow things as a matter of degree. According to Web of Science classification of documents, the disciplines of computer science, engineering, and mathematics exhibit solid positions in recognizing the works published in *FSS*. In addition, some publications from the subjects of automation control systems, operations research, management science, science technology, business economics, environmental sciences ecology, instruments instrumentation, and mechanics also pay substantial attention to *FSS* publications. A comparative analysis of subject categories of documents citing works published in *FSS* indicates that the share of scholarly works other than computer sciences and mathematics increased from 63.19% from 1989 to 1999 to 66.49% from 2000 to 2018. In sum, *FSS* has attracted worthy and wide scholarly attention with increasing diversity.

Results of cocitation network analysis

FSS has become a leading venue for fuzzy scholarship originating worldwide. In this section, to provide a deep analysis of the knowledge domain, we develop cocitation networks of leading authors, sources, and references cited in *FSS*. In doing so, the bibliographical connections are visualized and illustrated using VOSviewer software.

Cocitation network of most cited authors

Cocitation is the frequency with which two publications are cited together. The cocitation network analysis is useful in the identification of the most influential scholars. Figure 4 depicts the cocitation network of the most influential authors cited in *FSS* at least 25 times. This network was constructed using the fractional counting method (FCM). A total of 670 researchers meet the threshold among 23,544 researchers. In this network, 10 clusters were framed, represented by colors of nodes, with 43,778 links and 25,519.52 total link strength (TLS). In Figure 4, every node represents one cited author, and a highly cited author is represented most prominently. The size of a node is defined in direct accordance with the total number of citations of an author. The edges between two nodes indicate that these two authors are cocited and the thickness of an edge increases with weight of the link. A cursory look at Figure 4 exhibits that D. Dubois is the biggest node. It means that this author is most cited in *FSS*.

The top 10 cited authors and sources, along with their citations, links, cluster identification number, and TLS, are listed in Table 7. The authors are ranked in terms of TLS in descending order. It is evident from Table 7 that D. Dubois has been cocited with 604 authors that form the TLS of 1,933.4.

The second-largest node is L. A. Zadeh. This leading author is cocited with 646 authors that resulted in a TLS of 1,793.3. Zadeh was a world-famous computer scientist. R. R. Yager, U. Hohle, P. Hajke, E. P. Klement, and B. De Baets followed. Zadeh and Yager also received second and third rank in terms of TLS of cocitation in *FODM*. Also, Yager is a most productive author and the current editor-in-chief in another leading journal close to the scope of *FSS: International Journal of Intelligent Systems*. Furthermore, it can be seen from results presented in Tables 2 and 7 that three leading authors of *FSS*, namely De Baets, Dubois, and Klement, have also found positions in the list of top 10 cited authors in this journal.

A comparison of estimates of TLS obtained using the FCM with that of the full counting method reported in the last three columns of Table 7 indicates that use of the FCM leads to a substantial increase in value of TLS of all authors listed here. It implies that the research cited in *FSS* is of a coauthorship nature rather than sole publications. In addition, the relative strength of the FCM was evident in terms of the celerity of the cocitation network of cited authors. The ranking of authors listed here, namely De Baets, Yager, and Hajke, also improved from ninth to seventh, fourth to third, and seventh to sixth position, respectively. These results sustain an earlier finding of Perianes-Rodriguez et al.[25]

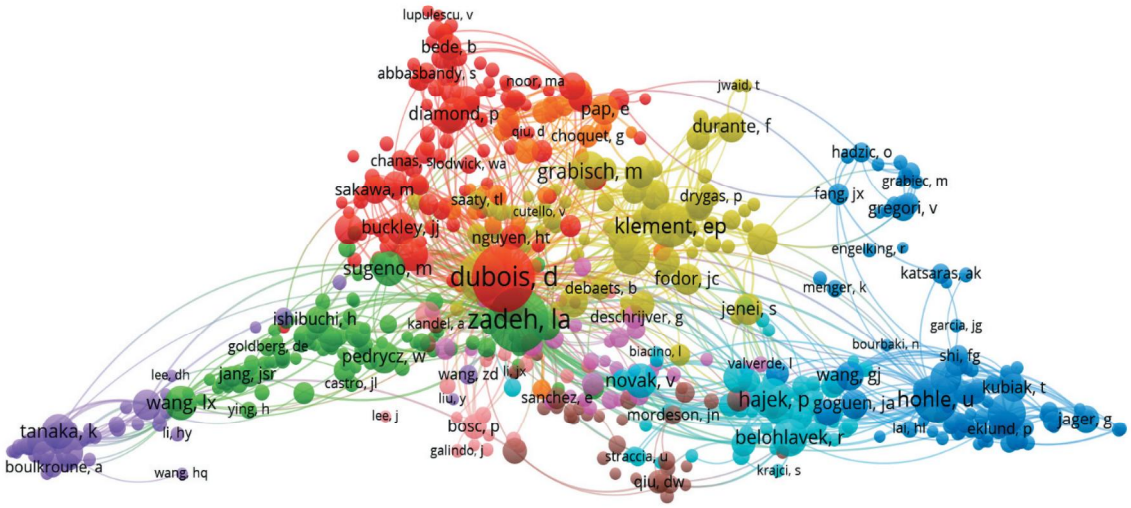

Figure 4. Cocitation network of cited authors.

Table 7. Most Cited Authors in *FSS*

Rank	Author	CI	C	Links	TLS	TLS^F	$CTLS^F$ (%)
1	Dubois, D.	1	2,265	604	1,933.4	40,315	95.20
2	Zadeh, L. A.	2	2,022	646	1,793.3	33,733	94.68
3	Yager, RR	4	1,026	508	867.1	16,940	94.88
4	Hohle, U	3	892	406	791.3	20,316	96.11
5	Klement, EP	4	816	525	770.3	16,087	95.21
6	Hajke, P	6	605	398	560.1	14,462	96.13
7	De Baets, B	4	527	410	489.2	10,717	95.44
8	Rodabaugh, SE	3	580	234	487.6	14,529	96.64
9	Grabish, M	4	563	372	468.4	9,554	95.10
10	Belohlavek, R.	6	482	343	383.5	9,254	95.86

CI = Cluster identification number. C = Citations. TLS = total link strength. TLS^F = Results obtained using Full Counting Method (FCM), $CTLS^F$ = Change in value of TLS due to use of FCM.

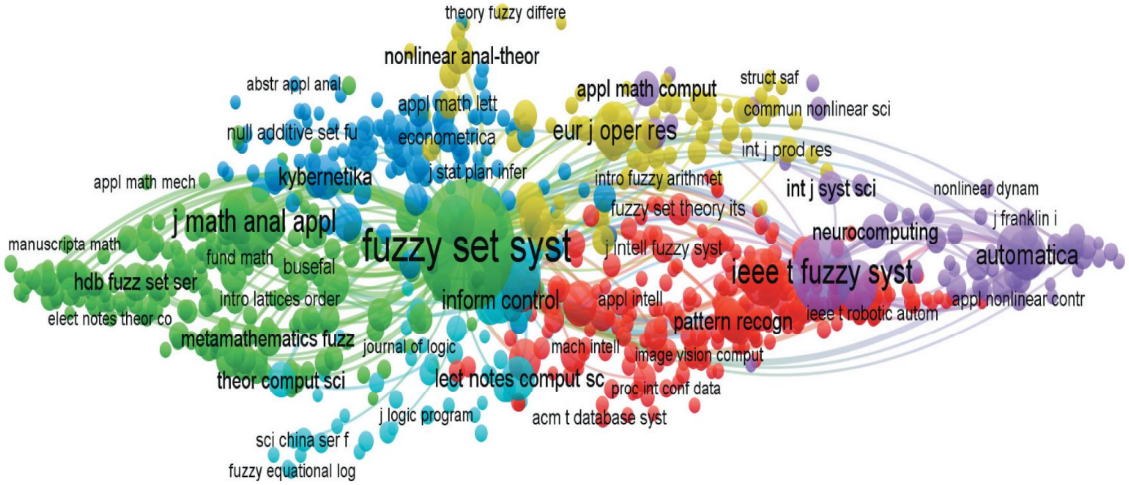

Figure 5. Cocitation network of cited sources.

Cocitation network of most cited sources

Recall that cocitation of sources is the frequency by which two sources get a citation in the same third source. The cocitation network of *FSS* is constructed employing association strength method using a threshold of a minimum of 15 citations, 779 sources meet the threshold among 17,072 sources. These sources formed six clusters with 74,007 links and 977,655 TLS. The cocitation network of the most cited sources in *FSS* with the 200 strongest connections is presented in Figure 5.

Table 8. Most Cited Sources in *FSS*

Rank	Source	CI	C	Links	TLS	IF
1	*Fuzzy Sets and Systems*	2	19,754	778	352,548	2.907
2	*IEEE Transactions on Fuzzy Systems*	5	4,230	724	105,846	8.759
3	*Information Sciences*	6	3,594	770	98,798	5.524
4	*Journal of Mathematical Analysis and Applications*	2	2,404	710	48,309	1.188
5	*International Journal of Approximate Reasoning*	1	1,076	715	30,709	1.982
6	*IEEE Transactions on Systems, Man, and Cybernetics: Systems*	1	1,294	678	29,285	7.351
7	*IEEE Transactions on Systems, Man, and Cybernetics: Systems B*	5	976	619	28,752	6.22
8	*European Journal of Operational Research*	4	1,150	569	28,011	3.806
9	*Automatica*	5	905	399	25,192	6.355
10	*IEEE Transactions on Neural Networks*	1	843	453	22,104	2.633

CI = Cluster identification number, C = Citations, IF = Impact factor, TLS = total link strength.

It clearly shows that *Fuzzy Sets and Systems* is the largest node. It means that *FSS* has strong connections with other sources. Moreover, as noted earlier, *FSS* has published a large number of documents. It increases the potential of citing other documents published therein. The quantitative information on the biggest 10 nodes of Figure 5 is presented in Table 8. The results reported in Table 8 are in accordance with Table 6. They indicate that connections of *FSS* with other influential international journals of fuzzy research are of the bidirectional type. In other words, most citing journals are cited in research published in *FSS* as well. As seen in Table 8, *FSS* is cocited in the documents published in this journal along with 778 sources 352,548 times.

In addition to *FSS*, *IEEE Transactions on Fuzzy Systems* (IF = 8.759), *Information Sciences* (IF = 5.524), *Journal of Mathematical Analysis and Applications* (IF = 1.188), and *International Journal of Approximate Reasoning* (IF = 1.982) are the top four journals that are cited by *FSS*. Other journals influencing the research published in *FSS* include *IEEE Transactions on Systems, Man, and Cybernetics: Systems* (IF = 7.351), *IEEE Transactions on Systems, Man, and Cybernetics: Systems B* (IF = 6.220), and *European Journal of Operational Research* (IF = 3.806). *IEEE Transactions on Fuzzy Systems* and *IEEE Transactions on Neural Networks* (IF = 2.633) are both published by the *IEEE Computational Intelligence Society*. According to Institute for Scientific Information (ISI) classification of fields of journals, most of the journals strongly linked with *FSS* belong to the disciplines of computer science, engineering, information technology, robotics, artificial intelligence, applied mathematics, cybernetics, and operations research.

Cocitation network of most cited references

The analysis of cocitation networks of the most cited references provides the most influential research and intellectual base of *FSS*. Figure 6 displays the references cocitation network of *FSS*. Only those references that have been cited at least 15 times are chosen to be displayed in this network; 696 sources meet the threshold among the 54,522 sources. In Figure 6, nodes are labeled with the first author of a cited document along with source and year of publication. Table 9 illustrates the 10 biggest nodes of the network shown in Figure 6. The biggest node is the name of the world-renowned computer scientist L. A. Zadeh.[26] It represents the pioneering paper of a new mathematical theory published in 1965: "Fuzzy Sets". This seminal research article, published in the journal titled *Information and Control*, is cited 506 times in *FSS* in the dataset being analyzed. It explores the basic properties and implications of fuzzy sets for solving real-world problems. This article has made a great contribution to development of various research fields related to fuzzy sets theory and its applications. This is the most cited research article of overall fuzzy research. This article also enjoys the same status in several other leading journals of fuzzy field, such as *Soft Computing, Information Sciences, Fuzzy Optimization and Decision Making*, and *Applied Soft Computing*.

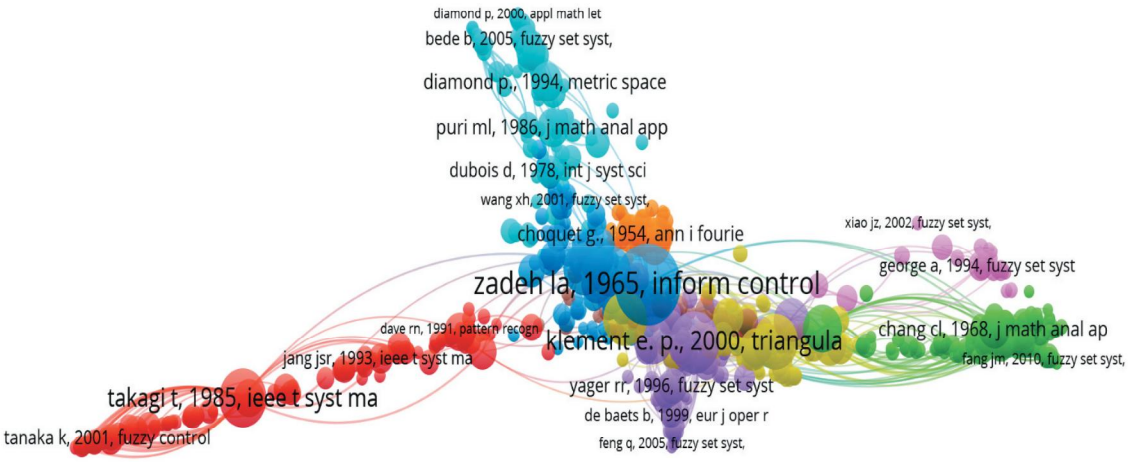

Figure 6. Cocitation network of cited references.

Table 9. Most Cited References in *FSS*

R	Title	DT	Author(s)	Source	Year	C	L	TLS
1	"Fuzzy sets"	Article	Zadeh, L. A.	*Information and Control*	1965	506	580	3,119
2	*Triangular norms*	Book	Klement, E. P., Mesiar, R., and Pap, E.	Netherlands: Springer	2000	297	426	2,590
3	*Metamathematics of fuzzy logic*	Book	Hájek, P.	Netherlands: Springer	1998	243	345	1,954
4	"L-fuzzy sets"	Article	Goguen, J. A.	*Journal of Mathematical Analysis and Applications*	1967	178	360	1,789
5	"The concept of a linguistic variable and its application to approximate reasoning—I"	Article	Zadeh, L. A.	*Information Sciences*	1975	218	385	1,701
6	*Fuzzy preference modelling and multi-criteria decision support*	Book	Fodor, J. C. and Roubens, M. R.	The Netherlands: Kluwer Academic Publishers	1994	173	319	1,624
7	*Fuzzy sets and fuzzy logic: Theory and applications*	Book	Klir, G. J. and Yuan, B.	Hoboken, NJ: Prentice Hall	1995	228	414	1,523
8	"Fuzzy identification of systems and its application to modeling and control"	Article	Takagi, T. and Sugeno, M.	*IEEE Transactions on Systems, Man and Cybernetics*	1985	265	190	1,459
9	*Probabilistic metric spaces*	Book	Schweizer, B. and Sklar, A.	New York: Dover Publications	1983	154	360	1,433
10	*Fuzzy sets and systems: Theory and applications*	Book	Dubois, D. and Prade, H.	New York: Academic Press	1980	207	409	1,290

R = Rank, DT = Document Type, C = Citations, L = Links, TLS = total link strength.

The second-most-cited document is a book, *Triangular Norms*, with 297 citations in *FSS* publications. It is one of the famous books by E. P. Klement, R. Mesiar (the all-time most productive author in *FSS*), and E. Pap. It focuses on applications of fuzzy logic and fuzzy sets using triangular norms. According to the Bookmetrix database, it has been cited 1,333 times within a time span of 19 years. This book also enjoys the status of the youngest reference on our list. Another book, titled *Metamathematics of Fuzzy Logic*, authored by P. Hájek and published by Springer, Netherlands, in 1998, occupies the third position. One more highly cited paper in fuzzy research, titled "The Concept of a Linguistic Variable and Its Application to Approximate Reasoning—I," is also frequently cocited in *FSS*.

Another book on our list, titled *Fuzzy Sets and Systems: Theory and Applications*, authored by D. Dubois and H. Prade (with a foreword by L. A. Zade) is one of the all-time most cited books in the overall field of fuzzy research. A handful of other publications are also cited frequently: "Fuzzy Identification of Systems and Its Application to Modeling and Control" and *Probabilistic Metric Spaces*. As seen in Table 9, most of the top-cited references (60%) in *FSS* are books rather than articles. It is interesting to note that four of the most frequently cocited documents are single-authored while six documents are coauthored.

Results of cooccurrence network analysis of keywords

The keywords cooccurrence network of a journal helps in the identification of main themes that are focused therein. The clusters of keywords of high relevance can be interpreted as research themes. Out of 12,764 keywords, 476 meet the cooccurrence threshold of 10 times. The highly connected keywords that appeared in *FSS* formed seven clusters with 12,118 links having a TLS of 24,939. Figure 7 displays a simplified keyword network with the 500 strongest links. Each cluster is represented by a color of nodes of keywords. As shown in Figure 7, several keywords, such as sets, design, system, model, fuzzy control, stability, logic, nonlinear-systems, stabilization, and operators have been the most frequently used in the documents published in *FSS*. The statistical information of the 30 biggest nodes of the network shown in Figure 7 is presented in Table 10.

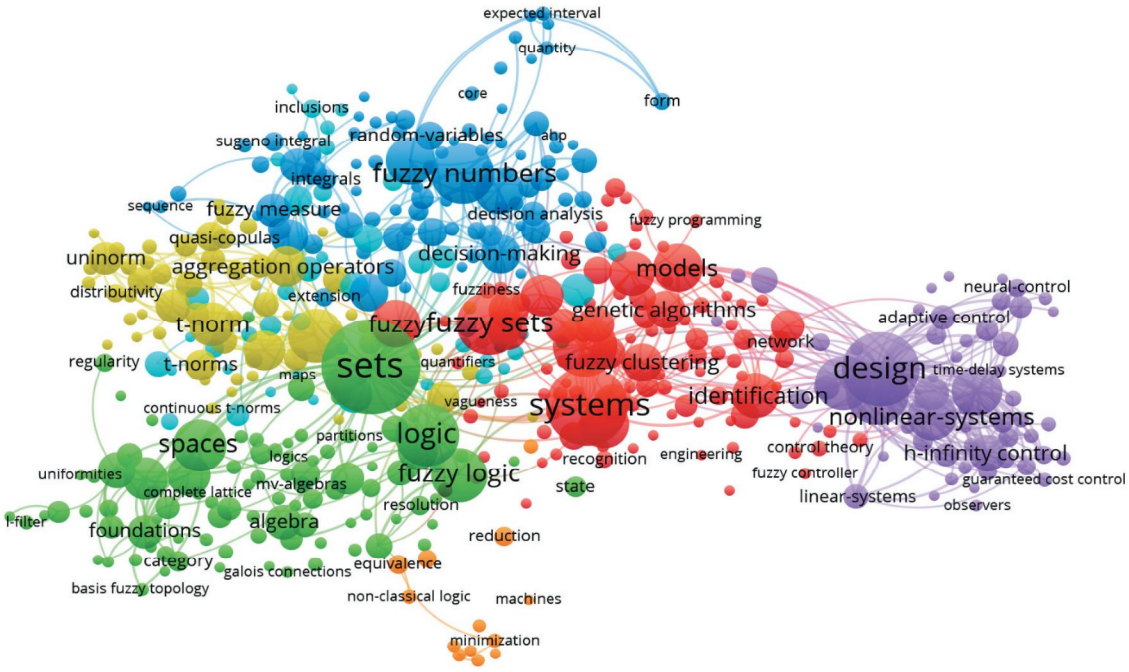

Figure 7. Cooccurrence of keywords in documents published in *FSS*.

Table 10. Most Frequently Used Keywords in *FSS*

R	Keyword	CI	F	D	TLS	R	Keyword	CI	F	D	TLS
1	Sets	2	300	302	1091	16	Numbers	3	158	154	439
2	Design	5	207	173	954	17	Algorithm	1	149	167	431
3	Systems	1	234	257	804	18	Optimization	1	105	149	423
4	Model	1	157	232	638	19	Uncertainty	1	68	172	402
5	Fuzzy control	5	150	129	616	20	Fuzzy logic	2	98	152	401
6	Stability	5	126	147	597	21	Spaces	2	100	133	401
7	Logic	2	156	239	565	22	T-norm	4	103	131	365
8	Nonlinear-systems	5	103	101	552	23	Information	1	92	145	362
9	Stabilization	5	109	96	546	24	Representation	3	83	162	349
10	Operators	4	128	190	494	25	Stability analysis	5	127	84	342
11	Fuzzy sets	1	158	200	439	26	Triangular norms	4	79	121	299
12	Fuzzy numbers	3	149	152	431	27	Decision making	3	76	123	295
13	Models	1	105	180	423	28	Foundations	2	63	82	290
14	H-infinity control	5	68	74	402	29	Fuzzy numbers	3	103	152	278
15	Identification	1	98	139	401	30	Fuzzy	1	103	165	271

R = Rank, CI = Cluster identification number, F = Frequency, D = Degree of association, TLS = total link strength.

The keywords are ranked in terms of their TLS. The top 30 keywords belong to the first five clusters. The most frequently used keyword is "sets," with 300 times cooccurrence. It occurred with 302 keywords, resulting in a TLS of 1,091. This keyword belongs to cluster 2 and is also strongly connected to themes represented by clusters 1, 3, and 4.

Cluster 1 primarily studies fuzzy system models, fuzzy clustering, genetic algorithms, neural networks, uncertainty management, optimization models, and identification models. Cluster 2 focuses more attention on fuzzy topology, fuzzy relations, fuzzy logic, and metric spaces. Cluster 3 mainly analyzes fuzzy numbers, fuzzy measures, fuzzy decision making, aggregation operations, convergence models, and fuzzy random variables. Cluster 4 places more emphasis on aggregation operators, triangular norms, copulas, fuzzy connectives, uninorms, and aggregation functions. Cluster 5 largely covers studies on fuzzy control, nonlinear systems, control design, stability analysis, and output-feedback control. Cluster 6 is grouped mostly by keywords related to fuzzy existence, fuzzy equations, and approximation. The final cluster consists of fuzzy equivalence, membership values, nonclassical logic, lattice value logic, fuzzy automata, machine, pumping lemma, and languages. As stated in the first section, *FSS* has recently put more emphasis on the publication of theme-based volumes.

Detection of bursting keywords

The bursting keywords detection analysis reveals changes that occurred in the relative importance of different themes over time.[27] In order to get a robust analysis about RQ3, bursting keywords that appeared in *FSS* are identified by employing CiteSpace software. The results are presented in Table 11. The body of Table 11 is coloured and there are bold red dots on the straight lines in the last column.

From 2000 to 2005, *FSS* focused on the publication of documents connected to fuzzy topology, fuzzy number, decision making, genetic algorithm, fuzzy control, fuzzy design, and stability. These bursting keywords can be termed as long-lasting hotspots in *FSS*. Two bursting keywords, namely fuzzy relation and topology, started in 2010 and were exhausted in 2012. From 2014 to 2018, the keywords algorithm, algebra model, logic, operator, fuzzy logic, uninorm, and space appeared frequently. Based on the foregoing discussion of this section, it may be concluded that the fuzzy research themes connected to copulas, aggregation function, uninorm, and space are the emerging hotspots in *FSS*.

Table 11. Top 25 Keywords with the Strongest Citation Bursts in Documents Published in *FSS*

Keyword	Strength	Begin	End	2000 - 2018
fuzzy topology	15.14	2000	2001	
fuzzy number	12.51	2000	2002	
dccision making	19.13	2000	2001	
genetic algorithm	16.45	2000	2002	
fuzzy control	29.04	2001	2005	
fuzzy	13.44	2001	2002	
design	4.27	2004	2005	
stability	10.35	2004	2005	
number	11.17	2007	2008	
nonlinear system	11.27	2008	2011	
foundation	13.03	2010	2011	
fuzzy relation	7.71	2010	2012	
topology	11.00	2010	2012	
representation	9.81	2011	2012	
copula	14.87	2013	2018	
aggregation function	15.56	2013	2018	
triangular norm	6.33	2013	2014	
algorithm	7.30	2014	2016	
algebra	10.54	2014	2016	
model	4.61	2014	2015	
logic	9.68	2014	2016	
operator	9.68	2014	2016	
fuzzy logic	4.17	2015	2016	
uninorm	14.53	2016	2018	
space	5.21	2016	2018	

Note. Citation burst indicates the degree of scholarly attention attracted by a research theme.

Growth prospects of *FSS*

In order to examine the growth prospects of this journal, the coauthorship networks of authors, institutions, and countries were analyzed. However, it was noted that all of these networks were quite sparse. With respect to the network of institutions contributing at least 10 publications in *FSS*, there were 16 clusters having 362 links and only 828 TLS. Similarly, the network of countries with publication of a minimum of five documents in this journal formed 10 clusters having 357 links and 1,375 TLS, which implies that *FSS* has large untapped potential. Regarding the coauthorship network of authors, a threshold level of 10 papers in *FSS* was fixed and the FCM was used. This network formed eight clusters, with 52 links and 99 TLS.

As noted earlier, most of the top-cited references in *FSS* are books. Clearly, the contribution of *FSS* to the field of fuzzy science can be improved by focusing more on the publication of book reviews. To do so, the book review policy can be clearly defined in the author information packet of *FSS*. As we mentioned earlier, *FSS* publishes a good number of documents. However, maintaining or increasing the number of works annually published in *FSS* is a challenge for this journal. The impact of works published in *FSS* was above the world average. Given the current average level of the IF (3.343) for the year 2020 of the journal, increasing its scientific influence is another challenge. It may be added here that a journal publishing a similar type of research on theory, design, and application of fuzzy systems, *IEEE Transactions on Fuzzy Systems*, has enjoyed a relatively much higher IF of 12.029 during the same period. Likewise, a comparative analysis of mainstream journals of fuzzy research indicates that OA documents have a relatively low

percentage in total publications of this journal. In order to increase the IF of this journal, the publication of documents in OA mode may be encouraged.[28] Recall from the temporal analysis of citations received by documents published in *FSS* presented earlier, this journal has experienced robust growth in the annual number of citations. However, the self-citation rate of the journal is found to be just moderate, with 4.87%. Attention should be paid to pathways to transform these challenges into opportunities for sustained growth of this journal. The above discussion is generalizable to a similar analysis on other subject areas.

Concluding remarks

FSS is one of the oldest and most outstanding global journals in the research domain of fuzzy mathematics. It has been published over the last four and a half decades. In order to examine the recent changes that occurred in productivity and the influence of *FSS* in the scientific community, this article analyzed the bibliometric information of recent publications of this journal published from 2000 to 2018. In doing so, cocitation networks of cited authors, sources, references, and cooccurrence networks of keywords used in *FSS* were developed employing the information visualization technology of VOSviewer. The robustness of the results of cooccurrence networks of keywords obtained using VOSviewer was strengthened by employing the burst detecting technique available in the CiteSpace software. The major contribution of this study is that we have provided a snapshot of the most influential research published in *FSS*. It is worth noting that some of the most influential research published in *FSS* is among the all-time most cited publications of overall fuzzy research.

During the last two decades, R. Mesiar and B. De Baets are the most productive authors in *FSS*, with a contribution of 83 and 50 articles, respectively. S. C. Tong is the most influential author, with 2,345 citations. The coauthorship network analysis indicated that Mesiar enjoyed the status of a high level of collaboration with other authors. The Slovak University of Technology Bratislava and Ghent University have emerged as the most productive institutions, with 119 and 118 publications, respectively. The University of Granada is the most influential institution, with 4,589 citations. The leading authors and institutions in *FSS* are among the most productive and influential authors and institutions of all-time research in fuzzy sciences. Arguably, the findings of this analysis are also useful to researchers who are looking to publish, collaborate, or identify trends in the literature. Similarly, the most influential research paper of fuzzy research, "Fuzzy Sets," authored by the founder of fuzzy set theory, L. A. Zadeh, dominates the list of most cited publications in *FSS* as well.

China, a developing country, is the most productive and influential country not only in *FSS* but also in overall fuzzy research. Spanish authors are growing remarkably the number of documents published. American scholars that were top contributors until 2000 have reached the third position during the period analyzed. An important empirical finding of this study is that the number of publications and h-index of *FSS* are relatively high in comparison to another mainstream journal of fuzzy research having a higher IF titled *Fuzzy Optimization and Decision Making*.

Another important finding is that *FSS* has strong bidirectional connections with other influential international journals of fuzzy research, such as *IEEE Transactions on Fuzzy Systems, Information Sciences, Journal of Mathematical Analysis and Applications, International Journal of Approximate Reasoning, IEEE Transactions on Systems, Man, and Cybernetics: Systems, Automatica*, and *IEEE Transactions on Neural Networks*. Being a respectable international journal, *FSS* has played an important role in shaping fuzzy research.[29]

Among other findings are that fuzzy research themes connected to copulas, aggregation function, uninorm, and space are the emerging fertile areas in *FSS*. The contributors and audience of *FSS* are dispersed across the world with many influential countries, institutions, and authors. *FSS* has witnessed an upsurge in its influence in recent years. The findings of the study are useful to researchers in information sciences and engineering to know the important research themes with a high potential for publication. Besides this, it is shown that *FSS* can be interesting not only for researchers in computer

sciences but in management sciences as well. Its thematic diversity is growing. The librarians may suggest this journal as study material for their users from different subject areas. Specifically, the worth of this analysis for other physical scientists and social scientists exists on the use of advanced mathematical methods of analysis in solving their research problems. The analysis of recent trends in the structure of *FSS* citations suggests that this journal can opt for the publication of scholarly works from natural and social sciences employing different fuzzy mathematical models. The important aspects of bibliometric analysis are demonstrated appropriately and the important associations of the most cited authors are conveyed. It may be instrumental in increasing researchers' understanding and satisfaction. Potentially, this study may also be used as a training resource for librarians. Similarly, its value for editors is to articulate policies focusing on types of publications that have considerably influenced the knowledge domain of this journal and to plan future directions. Readers can benefit from easy access to useful bibliometric information on the area of their interest. The strategies and methods employed in this piece of research could potentially serve as a good example for all stakeholders interested in a bibliographic analysis of other journals and investigation of recent citations trend in other areas of study.

Notes

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