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Bibliometric analysis of fuzzy theory research in China: A 30-year perspective

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ABSTRACT

The past half-century has witnessed fast development in the field of fuzzy theory (FT), however, few researches have focused on mapping the development of this area in China. Based on the samples of 12,936 publications authored by Chinese scholars on FT researches during the past 30 years, this paper intends to explore the patterns and dynamics by analyzing the geographic distribution of publications, international collaboration, research hot spot, subject categories and journals, and publication contributors. The results indicate that the scientific publications are highly unbalanced at regional levels in China, and the USA is China's most important partner in FT cooperative researches. Collaborations are not indispensable for high-quality research outputs in FT area. The existing researches in the field of FT from Chinese scholars focus primarily on Computer Science and Engineering. The emerging trends of FT researches from Chinese scholars have shifted away from basic FT researches to the applications, such as the areas of decision making, optimization, modeling and design.

1. Introduction

Since Zadeh authored the seminal paper titled "fuzzy sets" (published on *Information and Control* in 1965), fuzzy theory (FT) has attracted great attention and controversies [30,44]. FT mainly includes fuzzy set [31], fuzzy logic [70,82], fuzzy reasoning and fuzzy control [34,51]. At present, FT is a very popular and well established scientific field [39,83]. According to incomplete statistics, there are thousands of scholars from different disciplines participating in the research of FT theoretically or practically. The evidence from scholar Google shows that the number of the publications about FT has been well over two million. Many important academic journals focused only on fuzzy researches such as *Fuzzy Sets and Systems, IEEE Transactions on Fuzzy Systems* and *Fuzzy Optimization and Decision Making* were founded. Furthermore, some previous studies have focused the structures and patterns of the research area based on bibliometric measures. For example, López-Herrera et al. [43] studied the development of FT researches carried out by the Spanish community. Cobo et al. [19] proposed a method to analyze the thematic evolution of a given research field, and as example, they analyzed the FT area.

In the 70s of twentieth century, Chinese scholars began to study FT. Many Chinese scholars have done the massive research works on FT theoretically or practically. In the early 1990s, the founder of the FT, Zadeh had recognized that US, Japan, Europe, and China were the main force of FT researches. The scientific research outcomes from Chinese scholars have obvious influences in the home and abroad. Currently, tens of thousands of publications have appeared on Chinese and international professional journals. In the applications of FT, a lot of practical applications of research results from Chinese scholars have sprung up in the past few decades [73,84,89]. For example, Chinese scholars have successfully applied the FT to the weather forecasting [18,38], earthquake prediction [27,88], traditional Chinese medicine [21], blast furnace control [37], economics [23,28,72,77,91] and management [1,25,40,56–58,90]. Undisputedly, China has become a significant force in the FT scientific research community.

However, the current status of development about FT researches in China is still unclear, and so are the intellectual structures, research focus as well as emerging trends of FT in China. To fill these gaps, this study applies China's publications indexed in Science Citation Index Expanded (SCIE), Social Science Citation Index (SSCI), and Arts & Humanities Citation Index (AHCI)

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(1986–2015) to explore the current status and development trends of China's academic research performances in FT area based on bibliometric analysis methods.

Bibliometrics is the interdisciplinary science of quantitative analysis of all knowledge carriers by mathematical and statistical methods [7]. It is a comprehensive knowledge system which integrates mathematics, statistics and philology as a whole and pays attention to quantitative analysis. At present, more and more attention has been paid to this research. The most obvious advantage is that it allows scholars to investigate the specific research areas by analyzing the citations, co-citations, geographical distribution, and term frequency, thus drawing very useful conclusion [26,74]. In other words, it is possible to explore the inner publication structure and citation landscape in a research area [78,79]. At present, it has been widely used in research trend detection [2], author cooperative analysis [47,53,86], development of journal [10,13], development of the whole subject field [45], research topic clustering [22,54,55] and so on.

The objective of this paper is to adopt the bibliometric analysis methods to assess the current state and explore the development trends of fuzzy domain in China based on the literature data retrieved from Web of Science. The innovations of our research have three points: First, a large number of publications related to FT in China have been analyzed systematically and scientifically to find out the underlying information. Second, not only the statistical information based on different periods is used to analyze the structures and dynamics of China's FT publications, but also the links analysis and text mining based on social networks are used to explore further features. Third, the developments of China's FT publications are analyzed from different perspectives, which not only include the basic information, such as authors, journals, cited references, and subject category, but also include the research hot spot, international collaboration, and highly cited authors and papers. In addition, our research has some difficulties: On the one hand, the unifications of institutions need to be handled by combining variant institutions' names, and then the province of each institution needs to be recognized to make further analysis of regional distribution of China's TF research. On the other hand, the disambiguation of Chinese author names needs to be identified based on their full names and affiliations as some authors have same initials, even same full names.

This paper is organized as follows: Section 2 briefly describes the data source and methodology. Section 3 explores the intellectual structure of China's FT studies from co-authorship and geographical distribution analysis. Section 4 uses citation analysis technique and CiteSpace to visualize the highly cited references, disciplinary distributions, keyword co-word networks, journal co-citation networks and highly cited authors in FT research area from 1986 to 2015.

2. Data source and methodology

The literature data used in this study were downloaded from Web of Science: SCIE, SSCI, and AHCI. "Fuzzy" was used as the keyword to search the documents from 1986 to 2015 that contain this word in the abstract, title or keywords list. We set the CU= (China OR Peoples Republic of China OR Chinese NOT Taiwan), where CU represents country. Furthermore, the document types were limited to "article" and "review". In total, 12,936 documents met the selection criteria. Downloaded document included the title, publication date, keywords, journal information, the addresses of the authors and subject categories. All documents were downloaded on June 2, 2016, in plain text format.

Science mapping is an important procedure of bibliometrics. It aims at showing the structural and evolution of the scientific research field [9,19,48,49]. At present, there is a lot of software tools proposed to develop science mapping analysis [20]. CiteSpace II is the main tool used in this paper which is effective in information visualization and it was designed by Professor Chaomei Chen [11]. It has been used for obtaining quantitative information and visualizing information in special field [12,61], and recognized as one of the very influential software in the fields of bibliometrics and information visualization [71]. There is no doubt that the scholars from various disciplines have conducted their studies with the help of CiteSpace [75]. For example, Yu focused on the development of information aggregation operators and made a scientometrics review on this field [71]. Zhang et al. [85] visualized the development path of the researches on social media from a comprehensive perspective. Wei et al. [61] explored the geographic information systems knowledge domain with the help of CiteSpace. In order to identify the status of the public-private partnerships researches, Song et al. [50] used the CiteSpace to discover the trends and global patterns among the related publications. Chen et al. [14] detected the emerging trends and current status of the global scientific researches in the field of energy among 637 publications with the help of CiteSpace. All the above research results have shown that the CiteSpace is very effective in exploring the research trends and hot topics in a specific domain. Therefore, in this paper, we select the CiteSpace as the analyzing tool to discover the research trends and patterns among China's publications in the field of FT researches.

3. Development of FT

In this section, we study the concentration of FT researches in China at regional levels. It should be pointed out that the regions referred here are defined by province, autonomous region or municipality. The FT publications authored by Chinese scholars are shown in Table 1 by regions. For further exploring the structures and dynamics of China's FT publications, we split the whole period into three 10 year phases: 1986–1995; 1996–2005 and 2006–2015. Table 1 displays that the China' publications of FT vary widely across the whole country. Beijing, Jiangsu and Liaoning contributed 40.4% of all publications among the whole period. Furthermore, Beijing led with 2946 publications (20.36%) and it was followed by Jiangsu with 1613 publications. Liaoning ranked the third place and it contributed 1287 publications during 1986–2015. On the other hand, the ten least productive regions together contributed a total of 2.57% which is a very small share.

The statistical results indicate that the FT publications authored by Chinese scholars seem to increase substantially from 1986 to 2015. In three different stages, Beijing is always in the first place. The number of FT publications rose from 59 in the first period to 2314 in the third period. Jiangsu ranked the third place in the first two periods, however, it jumped to the second place in the third period with 1404 publications. Also, there are blanks of the FT researches in some regions. However, this phenomenon changed as time went on. During 1996–2005, the regions with blank only refer to Guizhou, Inner Mongolia and Tibet. Furthermore, the Tibet has become the only one, which is of very little contribution on FT developments during the third period.

The geographic information software was applied to visualize the publications distributions among different regions. The production of visualization was shown in Fig. 1 in detail. In Fig. 1, the red shades on the map represent the China's FT publication distributions from 1986–2015, the green shades with cylindrical shape represent three 10 year phases' distribution of top 20 regions ranked based on the total records during 1986–2015, and the three adjacent cylinders represent the three stages of 1986–1995, 1996–2005, and 2006–2015 from left to right, respectively. Also, the regions marked in white indicate the blanks of the FT researches, and both color depth and size of the cylinders can be used to measure the

Table 1
Regional distributions of FT publications (NS = National share).

Period	1986–2015			1986–1995			1996–2005			2006–2015		
Total records	14,470			315			1962			12,193		
Rank	Region	Number	NS	Region	Number	NS	Region	Number	NS	Region	Number	NS
1	Beijing	2946	20.36%	Beijing	59	18.73%	Beijing	546	27.83%	Beijing	2341	19.20%
2	Jiangsu	1613	11.15%	Sichuan	35	11.11%	Shanghai	219	11.16%	Jiangsu	1404	11.51%
3	Liaoning	1287	8.89%	Jiangsu	28	8.89%	Jiangsu	181	9.23%	Liaoning	1108	9.09%
4	Shanghai	1073	7.42%	Jilin	27	8.57%	Liaoning	170	8.66%	Shanghai	832	6.82%
5	Sichuan	886	6.12%	Hebei	26	8.25%	Sichuan	126	6.42%	Sichuan	725	5.95%
6	Hubei	771	5.33%	Shanghai	22	6.98%	Hubei	109	5.56%	Hubei	653	5.36%
7	Zhejiang	719	4.97%	Fujian	13	4.13%	Zhejiang	86	4.38%	Zhejiang	623	5.11%
8	Hunan	662	4.57%	Jiangxi	12	3.81%	Hunan	78	3.98%	Hunan	572	4.69%
9	Guangdong	607	4.19%	Hunan	12	3.81%	Guangdong	67	3.41%	Guangdong	530	4.35%
10	Shandong	448	3.10%	Zhejiang	10	3.17%	Jilin	59	3.01%	Shandong	410	3.36%
11	Hebei	430	2.97%	Guangdong	10	3.17%	Hebei	57	2.91%	Chongqing	394	3.23%
12	Chongqing	429	2.96%	Liaoning	9	2.86%	Tianjin	51	2.60%	Hebei	347	2.85%
13	Tianjin	361	2.49%	Hubei	9	2.86%	Shandong	35	1.78%	Anhui	320	2.62%
14	Anhui	350	2.42%	Yunnan	9	2.86%	Chongqing	32	1.63%	Tianjin	301	2.47%
15	Jiangxi	324	2.24%	Tianjin	9	2.86%	Anhui	26	1.33%	Jiangxi	296	2.43%
16	Fujian	244	1.69%	Shanxi	8	2.54%	Henan	20	1.02%	Fujian	215	1.76%
17	Jilin	242	1.67%	Anhui	4	1.27%	Shaanxi	19	0.97%	Shaanxi	197	1.62%
18	Shaanxi	216	1.49%	Guizhou	4	1.27%	Fujian	16	0.82%	Henan	183	1.50%
19	Henan	203	1.40%	Shandong	3	0.95%	Jiangxi	16	0.82%	Jilin	156	1.28%
20	Gansu	160	1.11%	Chongqing	3	0.95%	Gansu	10	0.51%	Gansu	149	1.22%
21	Shanxi	127	0.88%	Gansu	1	0.32%	Shanxi	9	0.46%	Shanxi	110	0.90%
22	Guangxi	109	0.75%	Qinghai	1	0.32%	Yunnan	9	0.46%	Guangxi	99	0.81%
23	Yunnan	94	0.65%	Guangxi	1	0.32%	Guangxi	9	0.46%	Heilongjiang	79	0.65%
24	Heilongjiang	84	0.58%	Heilongjiang	0	0	Heilongjiang	5	0.25%	Yunnan	76	0.62%
25	Guizhou	24	0.17%	Henan	0	0	Qinghai	4	0.20%	Xinjiang	21	0.17%
26	Xinjiang	22	0.15%	Hainan	0	0	Hainan	1	0.05%	Guizhou	20	0.16%
27	Qinghai	13	0.09%	Shaanxi	0	0	Ningxia	1	0.05%	Hainan	10	0.08%
28	Hainan	11	0.08%	Inner Mongolia	0	0	Xinjiang	1	0.05%	Inner Mongolia	9	0.07%
29	Inner Mongolia	9	0.06%	Tibet	0	0	Guizhou	0	0	Qinghai	8	0.07%
30	Ningxia	6	0.04%	Ningxia	0	0	Inner Mongolia	0	0	Ningxia	5	0.04%
31	Tibet	0	0	Xinjiang	0	0	Tibet	0	0	Tibet	0	0

range of percent. From Fig. 1, we can clearly find that the geographical concentrations of FT publications vary obviously. During 1986–1995 and 1996–2005, only a few provinces or municipalities such as Beijing, Shanghai, Sichuan, Jiangsu and Liaoning are active in FT publications. However, during the period of 2006–2015, more and more regions such as Hubei, Zhejiang, Hunan, and Guangdong, become very active in the production of FT knowledge.

As mentioned above, there are 12,936 documents that meet the selection criteria described in Section 2. Among these documents authored by Chinese scholars, 3435 publications were coauthored with foreign scholars. Table 2 illustrates the top 15 international partners in three different periods as well as the whole study period. In the first period (1986–1995), Chinese scholars cooperated with 13 countries on FT publications. The coauthored publications increased very fast in the next two periods, as the internationally coauthored publications rose to 440 and 2953 respectively. Table 2 also indicates that USA is the most important partner of Chinese scholars in FT researches. Throughout the whole research period, about 24.57% of the 3435 coauthored publications were involved at least one author from USA, and it was followed by Canada, the United Kingdom, Australia, Japan, Singapore and South Korea, with shares of 14.15%, 12.20%, 9.05%, 5.59%, 4.63% and 4.28%, respectively. The top 3 international collaborators accounted for more than 50% of all coauthored publications.

Fig. 2 shows the international co-authorship distributions from 1986 to 2015 and three decades. In Fig. 2, the red shades on the map represent the international co-authorship distributions of the whole study period, the green shades with different shapes represent three 10-year phases' distributions of top 15 countries listed in Table 2, and both color depth and size of the shapes can be used to measure the range of percent. Fig. 2 indicates that the co-authors with Chinese scholars were mainly from North America, Europe, Australia and Asia. In the first period, few foreign scholars co-authored with Chinese scholars in FT research area. However, this phenomenon was greatly changed in latter two decades. The percent of co-authors with Chinese scholars from Canada, the United Kingdom, and Australia increased evidently, whereas the percent of co-authors from Japan decreased.

4. Empirical researches of FT

4.1. Reference co-citation analysis

Reference co-citation analysis is an important approach to detect the structure and evolutionary path of a specified research area. Fig. 3 shows the network of the co-cited reference of the documents authored by Chinese authors on FT from 1986–2015, with the minimum spanning tree algorithm. From Fig. 3, we can find the most frequently cited work in FT area from Chinese scholars, the biggest node in Fig. 3 is Zadeh [80]. This ground-breaking work first proposed the concept and framework of FT. It has received great attention from scholars all over the world and it has more than 60,000 citations from Google scholar. The work of Takagi and Sugeno [52] entitled "*Fuzzy identification of systems and its applications to modeling and control*" is in the second place with 762 citations. This landmark work presented a fuzzy model of a system based on fuzzy implications and reasoning. The applications on water cleaning and converter in the steel making were also discussed. The third most frequently cited document was authored by Atanassov [3]. In this study, the author extended the FT and introduced the intuitionistic fuzzy set theory by adding the non-membership degree. The practice has shown that the intuitionistic fuzzy set is more powerful than traditional fuzzy set in modeling the uncertainty and fuzziness of the objective world in human mind [4,29,36]. Followed by Atanassov [3] is Zadeh [81] with 474 citations, which introduced the concept of linguistic fuzzy vari-

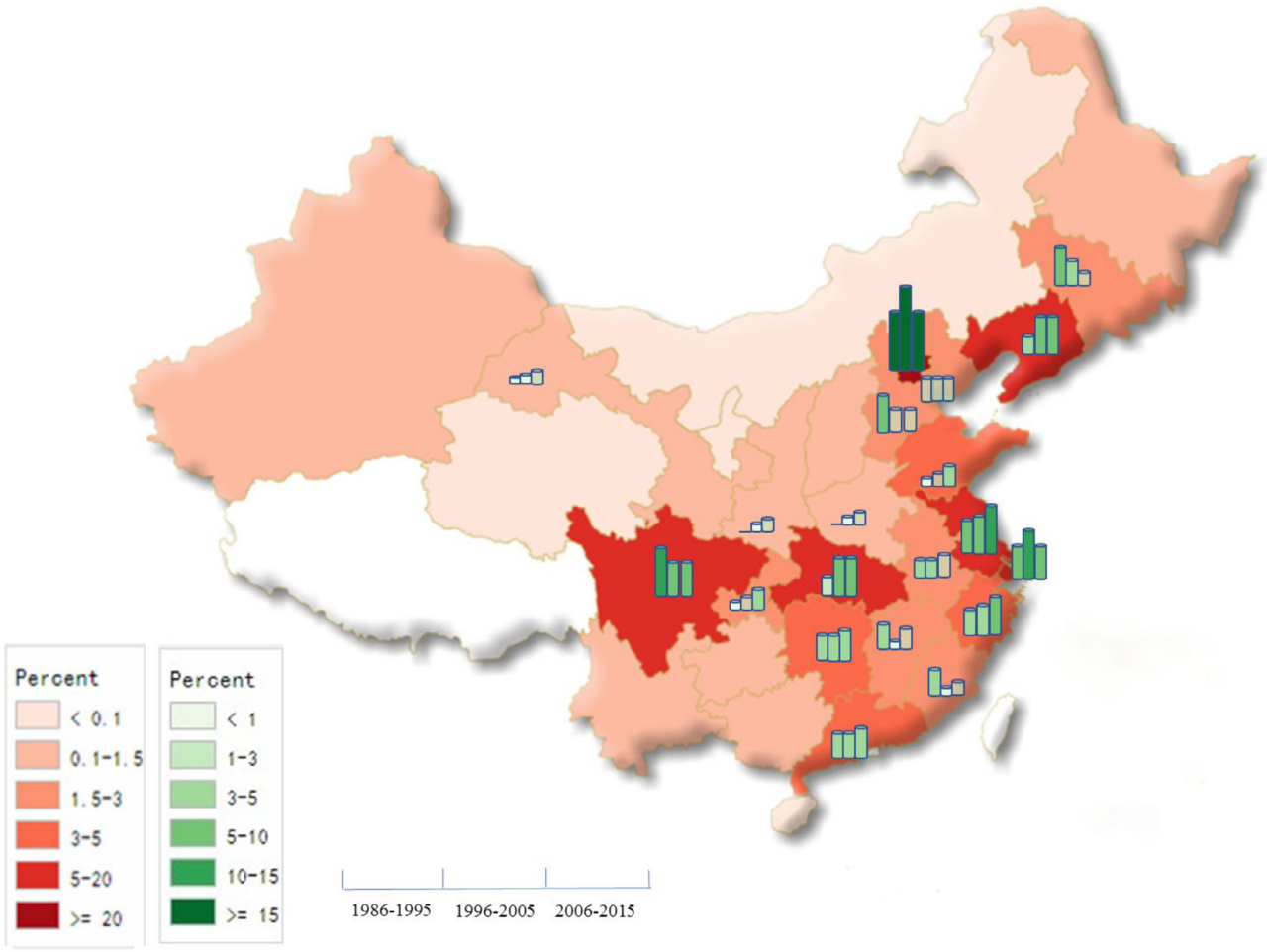

Fig. 1. China's FT publication distributions from 1986 to 2015 and three 10 year phases' distribution of top 20 regions.

Table 2
International collaborators of FT researches.

Period	1986–2015			1986–1995			1996–2005			2006–2015		
Total records	3435			52			440			2953		
Rank	Country	Number	Share	Country	Number	Share	Country	Number	Share	Country	Number	Share
1	USA	844	24.57%	USA	31	58.49%	USA	142	32.27%	USA	671	22.74%
2	Canada	486	14.15%	Japan	6	11.32%	The United Kingdom	47	10.68%	Canada	438	14.84%
3	The United Kingdom	419	12.20%	Singapore	4	7.55%	Canada	47	10.68%	The United Kingdom	369	12.50%
4	Australia	302	9.05%	The United Kingdom	2	5.66%	Japan	43	9.77%	Australia	289	9.79%
5	Japan	192	5.59%	Germany	1	1.89%	Singapore	28	6.36%	Japan	143	4.85%
6	Singapore	159	4.63%	France	1	1.89%	South Korea	25	5.68%	Singapore	127	4.30%
7	South Korea	147	4.28%	Austria	1	1.89%	Australia	22	5.00%	South Korea	121	4.10%
8	Germany	71	2.07%	Italy	1	1.89%	Germany	17	3.86%	Spain	55	1.86%
9	France	60	1.75%	Netherlands	1	1.89%	Belgium	17	3.86%	Saudi Arabia	55	1.86%
10	Spain	57	1.66%	Belgium	1	1.89%	North Korea	7	1.59%	France	54	1.83%
11	Saudi Arabia	55	1.60%	Norway	1	1.89%	Greece	6	1.36%	Germany	53	1.80%
12	Norway	52	1.51%	South Korea	1	1.89%	France	5	1.14%	Poland	49	1.66%
13	Poland	51	1.48%	Canada	1	1.89%	Switzerland	4	0.91%	Norway	49	1.66%
14	Belgium	50	1.46%				Netherlands	3	0.68%	Iran	48	1.63%
15	Iran	48	1.40%				Cameroon	3	0.68%	Pakistan	34	1.15%

able. The work of Pawlak [33] ranked the fifth place, and the author investigated the approximate operations on sets, and first proposed the concept of rough set. The sixth most frequently cited document was authored by Yager [67], which is a milestone in information aggregation area [15,68]. In this study, a very influential aggregation operator called ordered weighted averaging operator was proposed which has broad application background [65,69]. Atanassov and Gargov [5] ranked the seventh place with 308 citations, they extended the intuitionistic fuzzy set [3] and introduced the interval-valued intuitionistic fuzzy set which is a very useful method for modeling the fuzziness of the world [17,76]. Ranked the eighth place is a book, edited by Wang [59], this book focused on the adaptive fuzzy systems and control, and comprehensive analyzed the design and stability of the systems. The ninth most im-

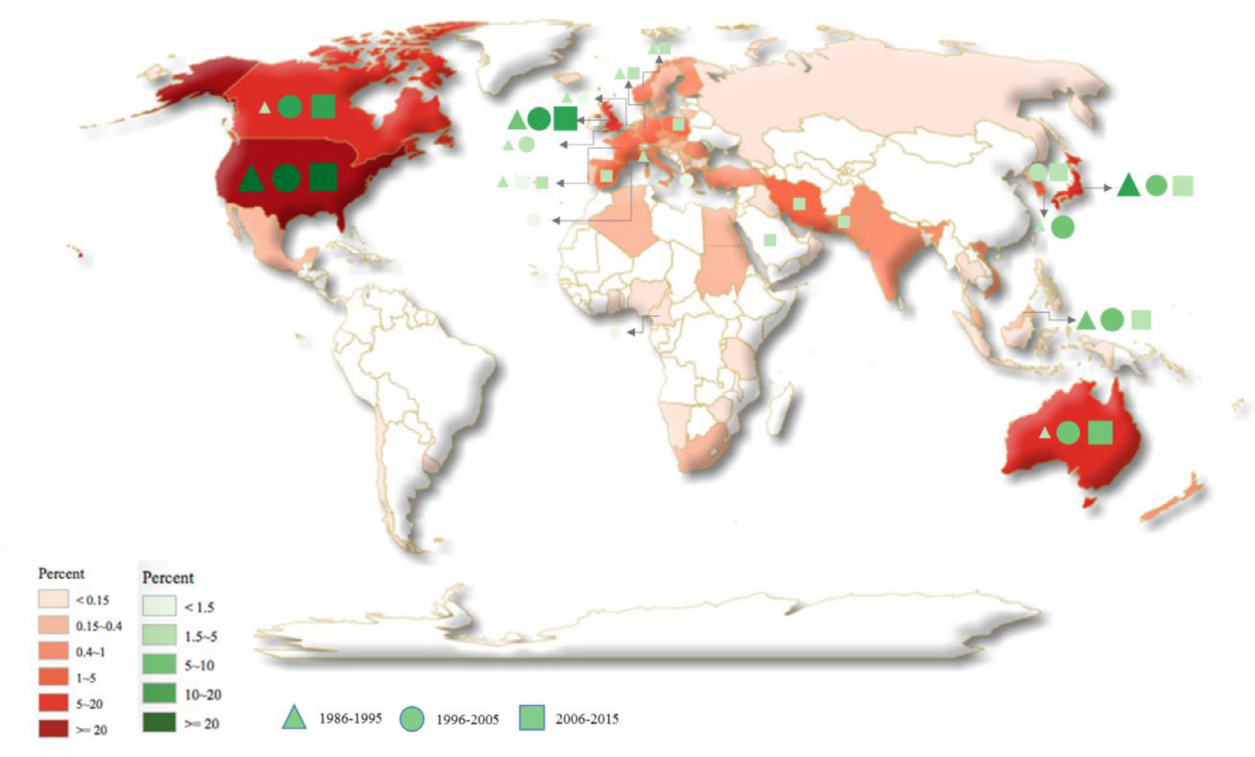

Fig. 2. International co-authorship distributions from 1986 to 2015 and three 10 year phases' distributions of top 15 countries.

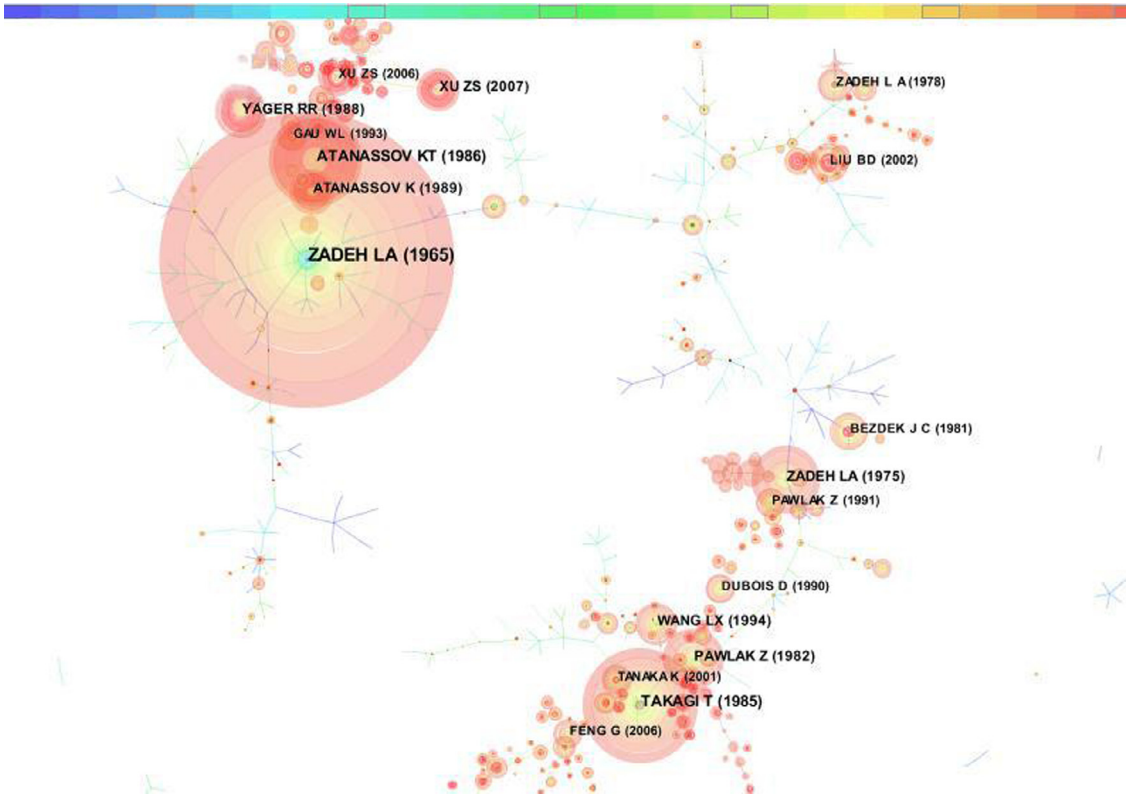

Fig. 3. Network of the co-cited reference o from 1986 to 2015.

portant document is Xu [63] which is a milestone in intuitionistic fuzzy information aggregation field. The author introduced a series of intuitionistic fuzzy information aggregation operators and applied them to multi-criteria decision making problem. The aggregation operators proposed by Xu [63] have been extended to different context [16,64,66,87]. It should be noted that Xu [63] is the only work published after 2000 among the top 10 documents. Ranked the tenth place is the work of Bezdek et al. [6], they studied the fuzzy c-Means clustering algorithms and exemplified by several examples.

Table 3 lists the top 10 most co-cited documents of FT in China. To our great surprise, only three multi-authored publications ap-

Table 3
The top 10 most co-cited documents of FT researches by Chinese scholars.

Frequency	Cited reference
1910	Zadeh [80]
762	Takagi and Sugeno [52]
607	Atanassov [3]
474	Zadeh [81]
405	Pawlak [33]
335	Yager [67]
308	Atanassov and Gargov [5]
289	Wang [59]
282	Xu [63]
273	Bezdek et al. [6]

Table 4
Terms and keywords during different periods.

Time span	High-frequency & centrality terms
1986–1990	fuzzy topological-space, fuzzy mapping, fuzzy classification
1991–1995	fuzzy number, fuzzy measure, fuzzy integral, fuzzy logic
1996–2000	system, fuzzy topology, neural network, fuzzy logic, genetic algorithm
2001–2005	System, neural network, fuzzy logic, fuzzy control, genetic algorithm, fuzzy number, design, nonlinear system
2006–2010	Uncertainty, nonlinear system, linear matrix inequality, system, model, design, algorithm
2011–2015	Aggregation operator, system, algorithm, uncertainty, numerical example, model, linear matrix inequality, optimization, system

peared and the remaining seven publications were all single authored. This also shows that collaborations are not always necessary to high-quality research output as seven out of ten were single authored.

4.2. Research hot spot evolution

Different themes prevail in different times. The research hot spot evolution detection is critical for grasping the track of the development of a certain theory. In order to get a macro-grasp on the development of FT in China, term and keywords analysis with centrality value and frequency are conducted based on CiteSpace. The entire study time was divided into six different periods (a 5 year period). In doing so, the research hot spot in different period as well as the obvious research direction transitions can be determined largely. The terms and keywords during different periods can be found based on text mining techniques and they were shown in Table 4.

As Table 4 shows, the research focuses have changed significantly from basic FT research to a comprehensive study. It can be found that in earlier studies the basic theories such as fuzzy topological-space, fuzzy mapping and fuzzy classification, as well as fuzzy integral and fuzzy logic were the main research focuses. However, these focuses have been shifted to applications, such as the areas of decision making, optimization, modeling and design.

4.3. Subject category analysis

Based on co-occurrence analysis of subject category, the top 20 ranked items are found and they were shown in Table 5. Computer Science was the most popular category of FT study in China during the past 30 years. Engineering ranked the second palace and it was followed by the subject category of mathematics, automation & control systems, statistics & probability, and operations research & management science.

The subject category co-occurrence network was shown in Fig. 4, which was constructed by 93 nodes and 258 edges. The node in Fig. 4 represents a subject category while an edge connecting two nodes expresses co-occurrence of the two subject categories. Fig. 4 conveys the similar meaning with Table 5. From Fig. 4, we can find that Computer Science, Engineering and Mathematics are the top three popular categories of FT research in China. Furthermore, we know that some nodes, shown by purple rings, indicate the high centrality values of the corresponding categories.

Table 5
The top ranked categories of FT in China.

Frequency	Categories	Frequency	Categories
1003	Computer science	55	Instruments & instrumentation
507	Engineering	50	Materials science
291	Mathematics	49	Science & technology - other topics
174	Automation & control systems	48	Water resources
156	Statistics & probability	47	Multidisciplinary sciences
109	Operations research & management science	40	Energy & fuels
89	Physics	40	Metallurgy & metallurgical engineering
75	Environmental sciences & ecology	38	Geology
74	Environmental sciences	36	Business & economics
58	Mechanics	36	Geosciences

In order to obtain a clearer picture of the category distribution in FT area, we conducted the work of the “category burst detecting”. The burst category can be used to reflect the research mainstream during the certain period. Based on the algorithm provided by CiteSpace, the top burst categories during the past five years (2011–2015) were presented in Table 6.

Table 6 conveys some interesting and important information about FT research in China. For example, the category of electrochemistry received special attentions from Chinese scholars during 2011–2012. As displayed in Table 6, more and more researches about the applications of FT to Social Sciences, Mathematical & Computational Biology and Economics appeared. These results not only indicate the current status of FT researches in China but also reflect the future trend in this area.

4.4. Keyword co-word analysis

The keywords can be regarded as the soul of an article, and the keyword co-word analysis can be used for detecting research topics as well as monitoring the research frontiers transitions of a certain knowledge domain [35,41]. It is well known that any article from WoS has one or more keywords. However, it should be noted that the articles published before 1991 did not provide the keywords. Therefore, the research period of keyword co-word analysis in this study was set as 1991–2015.

First of all, the process of standardization was taken to deal with the different words but stands for same meaning. For example, the words “system”, “systems”, “Systems” were all converted into “system” or “algorithm”, “algorithms”, “Algorithm” was all mapped to “algorithm”. Then, the keyword co-occurrence network between 1991 and 2015 was constructed based on CiteSpace. Based on the pathfinder algorithm which was provided by CiteSpace, the merged network consists of 440 nodes and 485 links were produced (Fig. 5). It should point out that a node expresses one keyword and the size of the node is determined by the co-occurrence frequencies of the keywords represented.

Excluding some words which are very broad such as design, model, systems, sets and fuzzy, the keyword “stabilization” has the biggest frequency. Other high frequency keywords include “algorithm (602)”, “optimization (596)”, “information (542)”, “uncer-

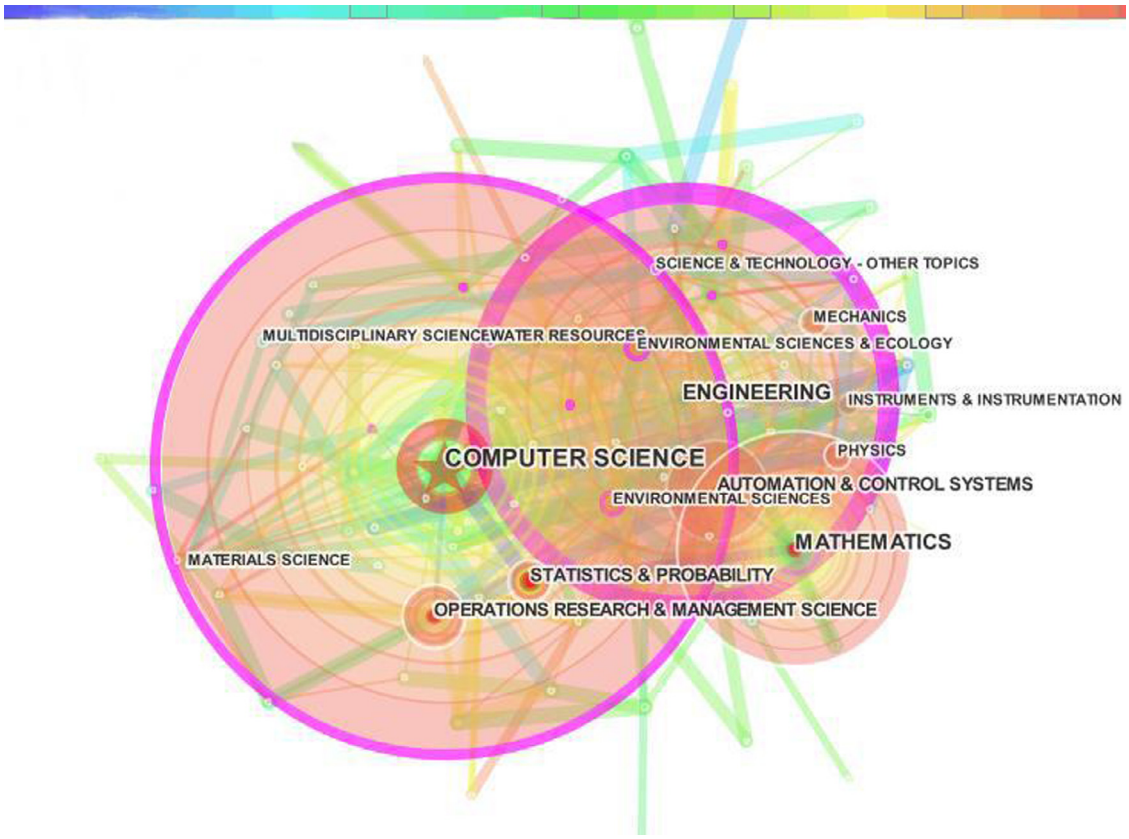

Fig. 4. Subject categories network in the field of FT.

Table 6
The burst categories of FT in China during 2011–2015.

Authors	Strength	Begin	End	1986–2015
Electrochemistry	4.5761	2011	2012	–
Meteorology & atmospheric sciences	9.3664	2012	2013	–
Mechanics	7.3644	2012	2013	–
Social sciences	3.6861	2013	2015	–
Mathematical & computational biology	5.6989	2013	2015	–
Social sciences- other topics	4.3723	2013	2015	–
Economics	5.9849	2013	2015	–

tainty (528)" and "fuzzy control (526)". Some other keywords such as "nonlinear-systems", "classification", "fuzzy logic", "genetic algorithm", "aggregation operator "and "decision making "have the frequencies of bigger than 300.

4.5. Journal co-citation analysis

The journal co-citation network in FT area can be plotted by CiteSpace [46]. Fig. 6 shows the journal co-citation network of 250 nodes and 230 links in the field of FT in China. The node size in the network means the citation frequency of the represented journal. Furthermore, we can find that some nodes in Fig. 6 were shown with purple rings. For examples, the nodes indicate the journals *Information Sciences* and *Information Control.* It should be noted that these nodes with purple rings represent high betweenness centrality. In other words, these nodes play an important role in connecting other nodes in the network. As Table 7 shows, *Information Sciences* has the biggest betweenness centrality value (0.91) and it was followed by *Information and Control* (0.8), *IEEE Transactions on Systems, Man, and Cybernetics: Systems* (0.77), *Automatica* (0.41), *IEEE Transactions on Automatic Control* (0.24) *and Fuzzy Sets and Systems* (0.2). Table 7 also shows that the journals in Computer Science and Engineering received far more attention. The Chinese scholars in FT field mainly came from the Computer Science and Engineering area. This research result coincides with the subject category analysis.

4.6. Author co-citation analysis

Author co-citation analysis is an important citation analysis method, since it was first proposed in 1981 [62], it has received wide attention and researches from scholars [24,60]. By drawing out the co-citation relations between the authors of the academic literature, author co-citation network can be obtained and used to guide the scientific research [8,32]. In the following, CiteSpace was adopted to draw out the author co-citation map on FT researches in China and it was displayed in Fig. 7. It consists of 286 nodes and 254 edges. Unsurprisingly, the node indicates that Zadeh LA is the biggest one among all the nodes. Furthermore, the nodes indicate that Zadeh LA and some others with purple rings express high centrality in FT researches from Chinese scholars. The most co-cited authors and their centrality values were shown in Table 8.

As shown in Table 8, Prof. Zadeh comes from UC Berkeley (USA) who was the founder of FT received the most co-citations among all the authors. Followed by Prof. Zadeh are Dubois D from Université Paul Sabatier (France), Xu ZS from Sichuan University (China), Yager RR comes from Iona College (USA), Takagi T from Tokyo Institute of Technology (Japan) and Atanassov KT from Bulgarian Academy of Sciences (Bulgaria). Among the 10 authors, Zadeh LA from UC Berkeley (USA), Wang LX from Xian Jiaotong University (China), Yager RR comes from Iona College (USA) and Xu ZS from Sichuan University (China) have the top four centrality value which means the researches of these four authors are more groundbreaking for Chinese scholars in FT area.

Fig. 5. The keywords co-occurrence network from 1991 to 2015.

Table 7
Distribution of core journals on FT in China.

Frequency	Centrality	Journal	Subject
6614	0.2	*Fuzzy Sets and Systems*	Computer Science, Mathematics, Statistics & Probability
4022	0.91	*Information Sciences*	Computer Science, Information Systems
4019	0.01	*IEEE Transactions on Fuzzy Systems*	Computer Science, Engineering
3936	0.77	*IEEE Transactions on Systems, Man, and Cybernetics: Systems*	Computer Science, Engineering
2232	0.14	*European Journal of Operational Research*	Business & Economics Operations Research & Management Science
2106	0.01	*Expert Systems with Applications*	Computer Science, Engineering Operations Research & Management Science
2095	0.8	*Information and Control*	Computer Science
1655	0.41	*Automatica*	Automation & Control Systems; Engineering, Electrical & Electronic
1492	0.19	*Journal of Mathematical Analysis and Applications*	Mathematics
1471	0.06	*IEEE Transactions on Neural Networks*	Computer Science, Engineering
1446	0.24	*IEEE Transactions on Automatic Control*	Automation & Control Systems, Engineering
1225	0	*International Journal of Approximate Reasoning*	Computer Science
1218	0	*Applied Soft Computing*	Computer Science
1132	0.01	*Computers & Mathematics with Applications*	Mathematics
1132	0.04	*International Journal of Intelligent Systems*	Computer Science
1059	0.15	*Knowledge-Based Systems*	Computer Science
1025	0	*International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems*	Computer Science
1003	0	*Lecture Notes in Computer Science*	Computer Science
988	0.1	*Pattern Recognition*	Computer Science, Engineering
950	0	*International Journal of General Systems*	Computer Science, Engineering

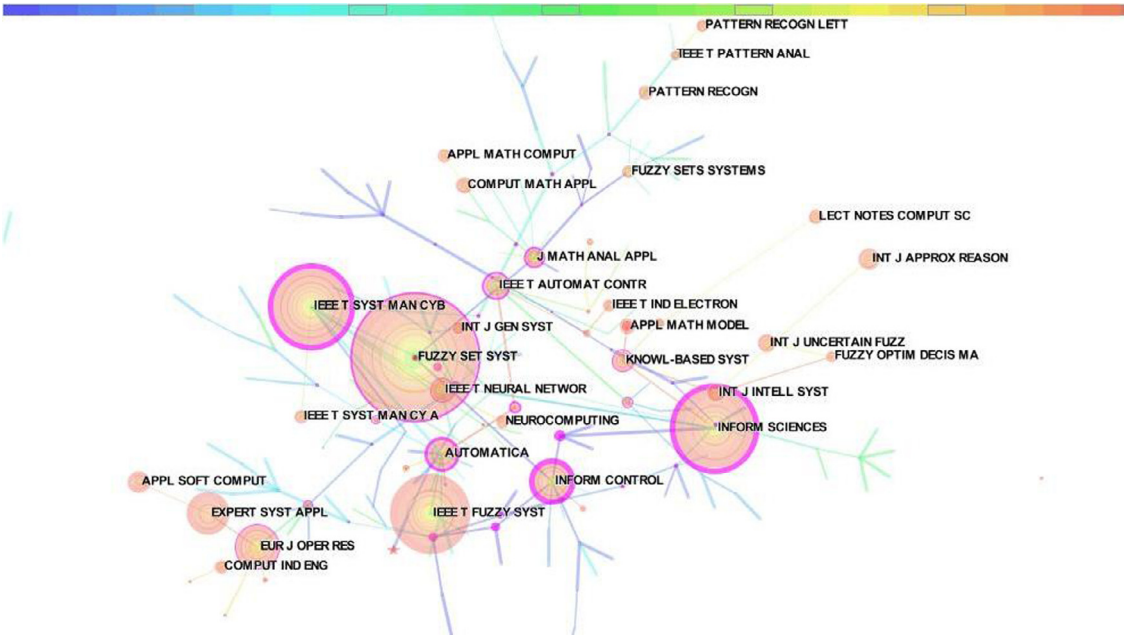

Fig. 6. The journal co-citation network from 1986 to 2015.

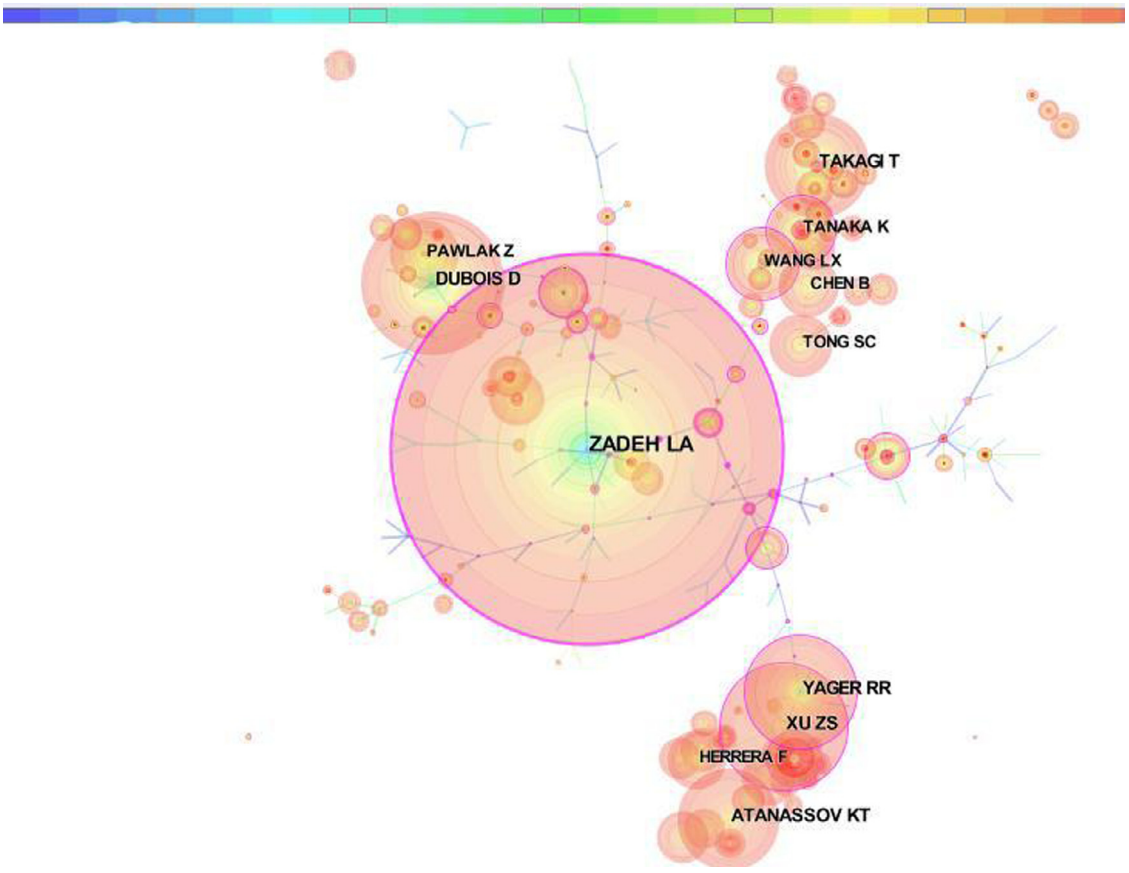

Fig. 7. Author co-citation network of FT research in China.

4.7. Highly cited Chinese authors and papers

Scholars from all parts of China contributed the fuzzy theory research. Table 9 shows the top 10 Chinese authors according to the total citations (TC) in fuzzy theory area. A variety of indicators are used to express the characters of these productive and influential authors totally and objectively, such as the institution, TC, total publication (TP), TC/TP, number of ESI publications (TP(ESI)), total publication in recent three years (2004–2016) (TP_3), total citations in recent three years (TC_3).

Table 10 presents the 10 most productive institutions and journals in this area according to the TP (ESI). Besides, many other in-

Table 8
The top 10 frequency cited authors.

Author	Frequency	Centrality	Institution
Zadeh LA	2976	0.63	UC Berkeley, USA
Dubois D	1147	0.1	Université Paul Sabatier, France
Xu ZS	987	0.23	Sichuan University, China
Yager RR	911	0.28	Iona College, USA
Takagi T	858	0	Tokyo Institute of Technology, Japan
Atanassov KT	806	0.04	Bulgarian Academy of Sciences, Bulgaria
Wang LX	569	0.3	Xian Jiaotong University, China
Pawlak Z	560	0.05	Polish Academy of Sciences, Poland
Tanaka K	558	0.21	University of Electro-Communications, Japan
Tong SC	513	0.04	Liaoning University of Technology, China

Table 9
The top 10 highly cited Chinese authors.

Rank	Name	Institution	TC	TP	TC/TP	TP(ESI)	TP_3	TC_3
1	Xu Zeshui	Sichuan University	235	9971	42.43	43	114	1403
2	Tong Shaocheng	Liaoning University of Technology	199	8147	40.94	41	73	1858
3	Shi Peng	Harbin Engineering University	147	6176	42.01	37	66	1911
5	Li Yongming	Shaanxi Normal University	170	4910	28.88	25	52	1377
6	Huang Guohe	Beijing Normal University	260	4236	16.29	1	81	356
7	Wei Guiwu	Sichuan Normal University	50	2454	49.08	18	19	359
8	Li Dengfeng	Fuzhou University	75	2415	32.20	5	20	153
9	Li Yongping	Beijing Normal University	130	1676	12.89	0	57	293
10	Chen Xiaohong	Central South University	123	1565	12.72	20	92	102

Table 10
Ten institutions and journals with most fuzzy ESI publications in China.

Rank	Institution	TP(ESI)	TC(ESI)	TC(ESI)/ TP(ESI)	Journals	TP (ESI)	TC(ESI)	TC(ESI)/ TP(ESI)	IF	Subject category
1	Harbin Institute of Technology	46	5914	128.57	IEEE Transactions on Fuzzy Systems	87	9707	111.57	7.671	Computer Science, Artificial Intelligence;Engineering, Electrical & Electronic
2	Liaoning University of Technology	43	4659	108.35	Information Sciences	46	4166	90.57	4.832	Computer Science, Information Systems
3	Southeast University	28	3218	114.93	Knowledge-Based Systems	31	2271	73.26	4.529	Computer Science, Artificial Intelligence
4	Central South University	26	1043	40.12	IEEE Transactions on Cybernetics	29	1886	65.03	7.384	Computer Science, Artificial Intelligence;Computer Science, Cybernetics
5	Bohai University	26	2097	80.65	Expert Systems with Applications	17	1513	89.00	3.928	Computer Science, Artificial Intelligence;Engineering, Electrical & Electronic;Operations Research & Management Science
7	Sichuan University	20	825	41.25	Applied Soft Computing	14	917	65.50	3.541	Computer Science, Artificial Intelligence;Computer Science, Interdisciplinary Applications
8	Northeastern University	16	1090	68.13	IEEE Transactions on Systems Man and Cybernetics Part B Cybernetics	10	1646	164.60	6.22	Automation & Control Systems;Computer Science, Artificial Intelligence;Computer Science, Cybernetics
9	PLA University of Science and Technology	15	1713	114.20	Fuzzy Sets and Systems	10	937	93.70	2.718	Computer Science, Theory & Methods;Mathematics, Applied;Statistics & Probability
10	Northwestern Polytechnical University	15	580	38.67	Journal of Intelligent Fuzzy Systems	9	485	53.89	1.261	Computer Science, Artificial Intelligence

dicators are also included to describe these influential institutions, such as total citation of these ESI publications (TC (ESI)), TC (ESI)/ TP (ESI). As regards the productive journals for the Chinese scholars based on TP (ESI), the impact factor (IF) and subject category are also presented to describe them. The Harbin Institute of Technology, Liaoning University of Technology and Southeast University are the three leading institutions regarding to fuzzy ESI publications in China. The top 3 productive journals for the Chinese scholars based on TP (ESI) were IEEE Transactions on Fuzzy Systems, Information Sciences and Knowledge Based Systems.

5. Conclusion and discussion

This study has made a comprehensive research on FT area in China from a bibliometric perspective. Our research results have indicated that FT has attracted more and more attention from Chi-

nese scholars over the past 30 years. However, despite a significant growth of FT publications in China, the distributions are highly unbalanced at regional levels. Beijing, Jiangsu and Liaoning contributed 40.4% of all publications from 1986 to 2015. Furthermore, Beijing led with 2946 publications and it was followed by Jiangsu with 1613 publications. On the other hand, the ten least productive regions together contributed a total of 2.57% which is a very small share. During 1986–1995 and 1996–2005, only a few provinces or municipalities such as Beijing, Shanghai, Jiangsu and Liaoning are active in FT publications. However, during the period of 2006–2015, more and more regions such as Sichuan, Hubei, Zhejiang, Hunan, and Guangdong, become very active in the production of FT knowledge.

The co-authors with Chinese scholars were mainly from North America, Europe, Australia and Asia. In the period of 1986–1995, few foreign scholars co-authored with Chinese scholars in FT research area. However, this phenomenon has greatly changed as time went on. USA is China's most important partner in FT cooperative researches in all three different periods.

The most frequently cited work in FT area from Chinese scholars is Zadeh [80]. Furthermore, among the top 10 most co-cited documents, only three are multi-authored publications and the remaining seven publications were all single authored.

The research focuses have changed significantly from basic FT research to a comprehensive study. In earlier studies the basic theories were the main research focuses. However, these focuses have been shifted to applications.

Among various disciplines, Computer Science and Engineering are the most popular ones in the field of FT research from Chinese scholars. More and more researches about the applications of FT to Social Sciences, Mathematical & Computational Biology and Economics have appeared in recent years.

This study has some shortcomings, such as the selected database, SSCI, SCIE and AHCI, favors English-language journals ([42]; Tang and Shapira, 2011). In our constructed database, only less than one percent of FT publications were not written in English. Therefore, this may underestimate the research status since some excellent FT publications authored by Chinese scholars were written in Chinese.

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