A Bibliometric Profile of Research on Rough Sets

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Abstract. Rough sets theory is a powerful mathematical tool for modelling various types of inexact, incomplete or uncertain information. Rough sets theory and its applications have attracted significant attention among researchers and extensive research has been carried out since it was first proposed by Pawlak in 1982. This paper presents a panorama of rough sets and quantitatively analyzes the developments of rough sets research by scientometrics approach. The bibliometric analysis is conducted based on 11833 Web of Science indexed papers published from 1982 to 2018. The science mapping tool, VOSviewer, is employed to cluster the documents and to assist in summarizing the important publications over the last ten years. The results are presented in the following aspects: development stages over the recent two decades, thematic structure of publications, citation distribution on subjects, core journals and conferences, international research collaboration profiles and top scholars. The results can benefit the scholars who want to go further in future research of rough sets.

Keywords: Rough sets · Bibliometric analysis · Research theme · Institutes performance · Cooperation network · Scholars distribution

1 Introduction

1.1 A Subsection Sample

Rough sets theory (briefly, RS) was proposed by Pawlak in 1982. Many complicated problems in economics, engineering, environmental science, medical science and social science may not be successfully solved because of various uncertainties arising in these problems. Motivated by the practical needs, RS models are developed to extract knowledge from incomplete, inaccurate and uncertain data sets.

The brilliant approach to classifying objects with their features and the introduction of approximation spaces can cope with large scale and diverse data easily. RS enables dealing with data granularity, which establishes the foundations of granular computing and provides an incisive approach to pattern recognition.

In the light of dealing with practical problem effectively, many researchers and practitioners have been imparted the study of hybridizations combining RS with other mathematical structures that are distinct but closely related. The RS blending with

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fuzzy sets, soft sets and neural network has been studied in recent years and some hybrid uncertain models occur [1]. Pawlak [2] has listed a wide range of applications of methods based on RS including machine learning, pattern recognition, data mining, knowledge discovery, bioinformatics, medicine, multicriteria decision making [3], signal processing, image processing, hierarchical learning, ontology approximation.

This paper presents a bibliometric profile of RS and quantitatively analyzes the developments of RS research by scientometrics approach. We will carry out bibliometric analysis to gain more insights in the domain of RS.

2 Data Source and Methodology

Bibliometric analysis helps to identify the influential works and to reveal some relations between academic entities. By adopting bibliometric analysis researchers will easily locate their positions in the research area and find new points for future research. The bibliographic metadata of literatures provided by publishers have abundant information for statistical treatment to evaluate the research performance of researchers, journals, countries and institutions [4–6]. Bibliographic coupling analysis is often used to outline the publications in a certain field [7, 8]. When two articles reference a common third article in their bibliographies, the two articles have bibliographic coupling, indicating that they study a related subject matter, and the similarity of their bibliographies can be defined as "coupling strength". The more citations to other articles they share the higher coupling strength they have.

The bibliometric maps in this paper are constructed by VOSviewer (www.vosviewer.com). It can be used to cluster publications and to analyze the resulting clustering solutions related to citations, co-occurrence (i.e. co-authorship and co-institute), bibliographic coupling and co-citations in bibliometric map.

The bibliographic data are obtained through the Clarivate Analytics' Web of Science™ (WoS), which contains 7 core collection databases, including SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH. To analyze the distribution characterizations of the literatures, the related information is extracted from particular fields of the metadata downloaded from WoS. We retrieve 11833 papers by the query as follows: TS = ("rough set$" or "rough fuzzy set$" or "rough soft set$") and PY = (1982–2018). We use the ($) in the search as a wild card character to make our search simpler and more comprehensive as it will track all possible forms of the terms used (i.e. set or sets).

3 Academic Development of RS

3.1 Development Stages

The line in Fig. 1 shows the number of RS paper publications by year from 1999 to 2018. The documents can roughly be classified into two types, proceeding papers and journal articles, as indicated by bars in Fig. 1. In fact, we used "Meeting Abstract OR Meeting Summary OR Proceedings Paper" for searching proceeding papers, and

selected "Article OR Editorial Material OR Letter OR Review" to obtain journal articles, and found that few other document types left. If one paper is both labeled article and proceeding paper, it will be treated as article.

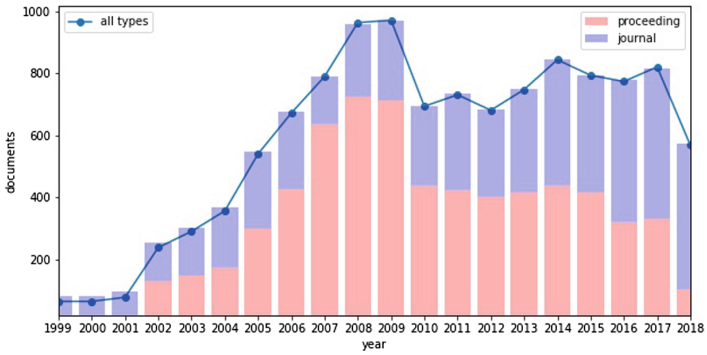

Fig. 1. RS publication year distribution in WoS.

As shown in Fig. 1, the number of articles published before 2001 is relatively small. There is a rapid growth from 2002 to 2009, and then the annual paper publication number drops below 800 and grows slowly but steadily from 2010 to 2018. Compared with that of the previous decade, the proportion of journal articles has increased and gradually exceeded that of conference papers in the 2010–2018 period. For these reasons, the period from 2002 to 2009 can be considered as a growth period of RS, and the 2010–2018 period can be interpreted as mature period. During the growth period many conferences have been held and publishing articles in journals is relatively difficult, while during the mature period journal articles have thrived.

3.2 Theme Clustering

To illustrate the general situation of original researches of RS in the last decade from 2009 to 2018 that covers the mature period, bibliographic coupling network of the documents is made by Vosviewer (Fig. 2). Bibliographic coupling of papers, as pointed out before, shows the relation between papers that citing at least one same other paper. This relationship provides the basis for topic clustering. It is proved to be an efficient approach for grasping the main themes of a research area of some scale.

As is shown in Fig. 2, every bubble shows its citations by the size. The nodes with less than 20 citations have been cut off to make the figure more readable. The articles published in the last three years have not got citations sufficiently. In order to make the newly published articles that are not sufficiently cited displayed fairly with the old ones, the papers' citations of each year are weighted by a factor calculated from the citation trends of the previous three years.

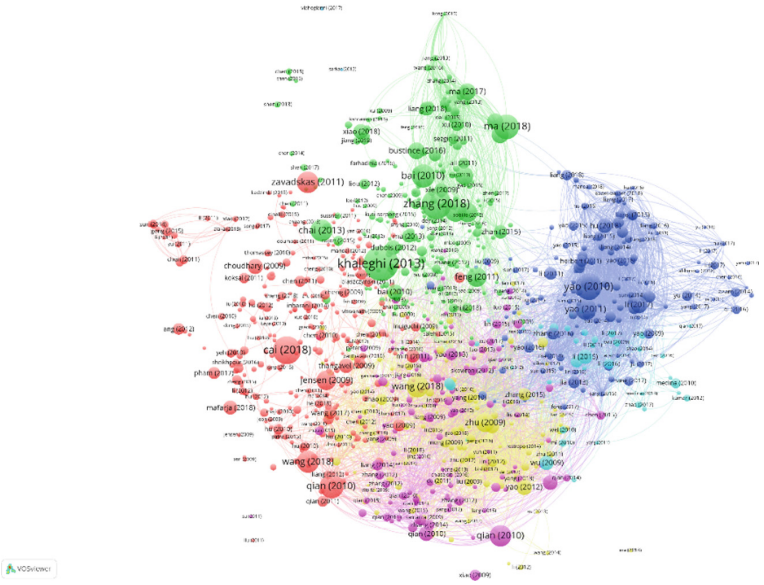

Fig. 2. Articles clustering by bibliographic coupling. (Color figure online)

Clusters with different colors reflect different themes of this area. We will explore and explain the themes of these clusters one by one by scanning the larger nodes in every cluster.

Red Cluster: Dimensionality Reduction and Its Application

One of the major limitations of the traditional rough set model in the real applications is the inefficiency in the computation of core attributes and reducts. Jensen and Shen [9] provided the approaches of fuzzy-rough feature selection for dimensionality reduction. Chen et al. [10] proposed a RS approach to solve feature selection problems successfully by using ant colony optimisation, which adopts mutual information based feature significance as heuristic information. Qian et al. [11] introduced a positive approximation framework to accelerate a heuristic process of attribute reduction. Wang et al. [12] proposed an index to characterize the discrimination of a neighborhood relation for their feature selection algorithm. He et al. [13] combined RS theory, data envelopment analysis and fuzzy artificial neural network to explore the effects of influencing factors on industrial energy efficiency. Cai et al. [14] improved the prediction of sensitive information by using RS approach to avoid inference attack for social network. Choudhary et al. [15] reviewed the multiple approaches of knowledge discovery and data mining applied in manufacturing process.

Green Cluster: Hybrids of RS

The RS hybridization with fuzzy sets has been studied much from early time because of the natural correlation between fuzzy sets and RS. Dubois and Prade [16] clarified the difference between fuzzy sets and RS and developed the concept of fuzzy RS to deal with numerical and fuzzy attributes. Yao [17] compared theories of fuzzy sets and RS

and pointed out that RS under set-oriented view are closely related to fuzzy sets. Wu et al. studied generalized fuzzy RS [18] and related approximation operators [19] in which both the constructive and axiomatic approaches are used. Yeung et al. [20] presented a unified framework for fuzzy RS theory and set up its mathematical foundation for extending its applications. Hu et al. [21] introduced a simple and efficient hybrid attribute reduction algorithm based on a generalized fuzzy-rough model that can keep or improve the classification power with very few features. Mi and Zhang [22] extended approximation concepts to generalized fuzzy lower and upper approximation operators.

Besides, another kind of hybrid uncertain model, soft RS can be observed in this cluster. Soft sets, introduced by Molodtsov [23] in 1992, are a special case of context dependent fuzzy sets. Maji et al. [24] first presented an application of soft sets in a decision making problem with the help of RS. Chen et al. [25] then compared the parameterization reduction of soft sets with the attribute reduction in rough set and improved the application of a soft set in a decision-making problem. Aktaş and Çağman [26] compared soft sets to RS and Feng et al. [27] expanded soft sets to rough soft sets by embedding RS. In recent years rough soft sets and soft rough sets are mainly used in decision making problems [28]. Feng et al. proposed the hybrid models rough soft sets [27] and soft RS [29]. Zhan et al. [30] merged RS, soft sets and hemirings to provide soft rough algebraic structures. They [31] also extended the notion of soft RS and rough fuzzy sets to study roughness in hemirings.

Blue Cluster: Three-Way View Decision

The three-way decision-theoretic RS model was proposed by Yao [32]. The three-way decisions theory considers a decision-making problem as a ternary classification one. The positive, negative and boundary regions are associated with different levels of uncertainty. Yao [33] discussed the advantages of three-way decision in probabilistic rough set models.

Li and Zhou [34] proposed a three-way view decision model based on decision-theoretic RS. Herbert and Yao [35] investigated the Game-theoretic RS to reduce the boundary region in the decision problem. Sun et al. [36] constructed a multigranulation fuzzy decision-theoretic three-way group decision making method. Li et al. [37] developed an axiomatic approach to characterize three-way concepts. The three-way decision model has been used in face recognition [38] and recommender system [39]. Yu et al. [40] investigated the method for automatically determining the number of clusters by the decision-theoretic rough set model. Qi et al. [41] presented the constructing of three-way concept lattices based on classical concept lattices. Jia et al. [42] provided the minimum cost attribute reduction method for decision-theoretic RS models.

The Rest Clusters

The remaining clusters focus on some special extensive research themes which have not been studied too much. The yellow cluster studies covering-based RS. In RS theory, relation-based RS and covering-based RS are two important extensions of the classical RS. Covering-based RS [43] is a successful generalization for the Pawlak's model to make use of non-equivalence relations. Zhang et al. [44] recently established some constructive methods of rough approximation operators to make the equivalence

relations in RS not too restrictive for practical applications. The pink cluster focuses on multi-granulation RS which was developed by Qian [45] to extend Pawlak's model to a multi-granulation RS model using multi-equivalence relations. In addition, a growing research interest of neighborhood RS [46] is observed in recent years for its effectiveness of dealing with data of multi-granularity [47]. Finally, the bright blue cluster is mainly concerned with formal concept analysis and RS.

3.3 Subject Distribution of Citations

The total number of citations to RS research articles is larger than 39,200 and is increasing quickly. The citations come from different subject areas in WoS. Some interesting areas are selected to reveal the extension of RS researches to the complicated world.

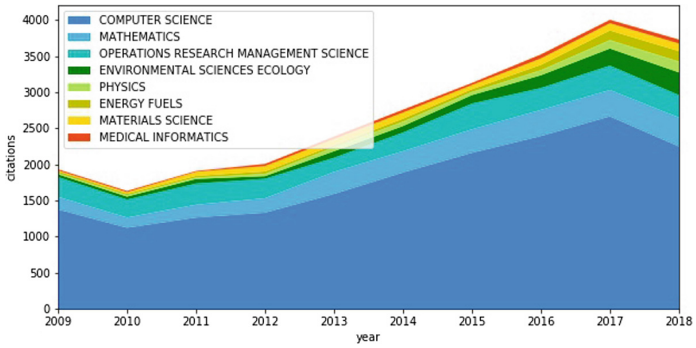

Fig. 3. Some research areas that citing RS from 2009 to 2018. (Color figure online)

Figure 3 shows some research areas with increasing RS research citations. Computer science and mathematics are the circumstances that give birth to RS. The other areas like management science and environmental science may give the application and development environments for RS. RS researches have been increasingly applied to power industry [48], natural resources sustainable utilization [49], medical diagnosis and prognosis [50] and synthetic materials design [51], etc.

4 Journals and Conferences Analysis

4.1 Core Journals

There are 4427 papers published on 778 journals in WoS from 1999 to 2018. The top 10 journals are listed in Fig. 4 and Table 1.

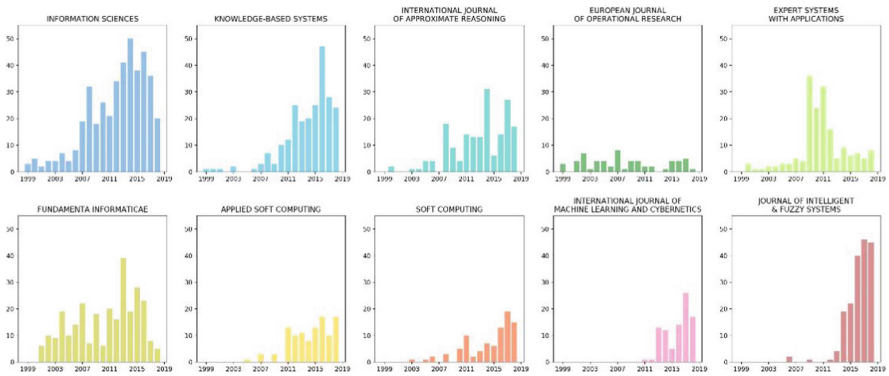

Fig. 4. Annual documents benchmarking for the top journals on RS researches.

The journals are chosen according to the total number of papers on RS, and the number of citations got over the period is also taken into consideration. The longitudinal coordinates are set to the same range so that the annual documents can be compared. The two periodicals, *Information Sciences* and *Knowledge Based Systems* are the mostly cited journals in RS researches. The number of documents on RS in these periodicals has an obvious growth trend in recent years.

The number of RS research articles in *Expert Systems with Applications* was relatively large over the particular period of 2009–2012, but it has remained at a low level in recent 6 years. In *Journal of Intelligent & Fuzzy Systems*, by contrast, the number of RS theory papers has thrived these years.

Table 1. Profile of the top journals.

Journal name	Documents	Citations	Journal IF	Quartile
INFORMATION SCIENCES	417	19156	4.305	Q1
FUNDAMENTA INFORMATICAE	279	2608	0.725	Q3
KNOWLEDGE-BASED SYSTEMS	229	4754	4.396	Q1
JOURNAL OF INTELLIGENT & FUZZY SYSTEMS	180	517	1.426	Q3
INTERNATIONAL JOURNAL OF APPROXIMATE REASONING	178	4744	1.766	Q2
EXPERT SYSTEMS WITH APPLICATIONS	172	4456	3.768	Q1
APPLIED SOFT COMPUTING	106	1825	3.907	Q1
INTERNATIONAL JOURNAL OF MACHINE LEARNING AND CYBERNETICS	89	543	2.692	Q2
SOFT COMPUTING	88	1041	2.367	Q2
EUROPEAN JOURNAL OF OPERATIONAL RESEARCH	61	4488	3.428	Q1

Table 1 gives an outline of the top journals and the last impact factors and the quartiles are listed. In addition to considering the fitness of the article to the subject of a journal, the international influence and status of a journal should also be taken into account.

4.2 Important Conferences

For computer science research, conference papers are sometimes more important than journal articles. There are about 4000 proceeding papers of RS recorded in WoS, including 2 highly cited papers in this period. The number of the proceeding papers is larger than that of the journal articles in WoS in the recent decade. But in the last decade, the conference papers are much more numerous than journal articles, which can be seen from Fig. 1.

The eight top conferences in RS research field are selected from 1999 to 2018 according to the number of papers, as shown in Table 2.

Table 2. Top conferences in RS research field from 1999 to 2018.

Conference name	Abbreviation	Papers
International conference on rough sets and knowledge technology	RSKT	377
International conference on machine learning and cybernetics	ICMLC	309
International conference on rough sets fuzzy sets data mining and granular computing	RSFDGrC	289
IEEE international conference on granular computing	GrC	226
International conference on rough sets and current trends in computing	RSCTC	216
International conference on fuzzy systems and knowledge discovery	FSKD	174
International joint conference on rough sets	IJCRS	128
IEEE international conference on fuzzy systems	FUZZ-IEEE	120

Proceeding papers have been indexed in these database: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH. For some conferences, the number of papers in WoS databases might be smaller than that published actually in the conferences. The quality of papers in a conference may affect their number included in the database. The annual heatmap of papers in the top eight conferences is shown in Fig. 5. The labels of the horizontal ordinate refer to the abbreviations in Table 2.

Some conferences have changed over the past two decades. Since 2015, IJCRS has integrated the four conferences, RSKT, RSFDGrC, RSCTC and RSEISP (whose full name is *Rough Sets and Intelligent Systems Paradigms*), which are the major threads of RS conferences. FSKD has been held as part of *International Conference on Natural Computation, Fuzzy Systems and Knowledge Discovery* (ICNC-FSKD) from 2016.

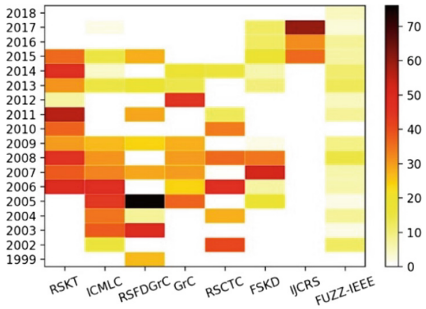

Fig. 5. Annual heatmap of the top conferences.

5 Main Institutes and Scholars of RS Research

5.1 International Collaborators

The collaboration between countries or regions is shown in Fig. 6. The line thickness of each pair of countries or regions represents the strength of the collaboration. The colors of labels represent the clusters which are calculated by their links' similarity in VOSviewer. If some countries or regions often link to each other or if they have the same links with the other nodes, they tend to be classified in the same cluster.

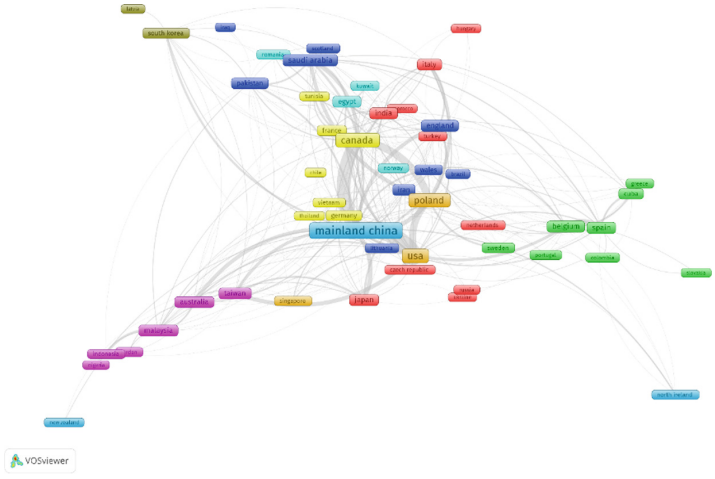

Fig. 6. Co-occurrence of country/region for RS research from 2009 to 2018.

In Fig. 6, we can see Mainland China, USA, Canada and Poland have established a tight group in the center, which features the close relationship of their cooperative RS research. Saudi Arabia England and Japan also have relatively strong partnership with China.

5.2 Main Institutes

Since more than half of the RS research articles are from China, the rankings of the institutions from other countries would be forced to sink. To avoid this, we select the top three influential institutes according to their citations in WoS for the eight top countries chosen from the map of Fig. 6, and these 24 institutes are compared in the number of documents and citations simultaneously in Fig. 7.

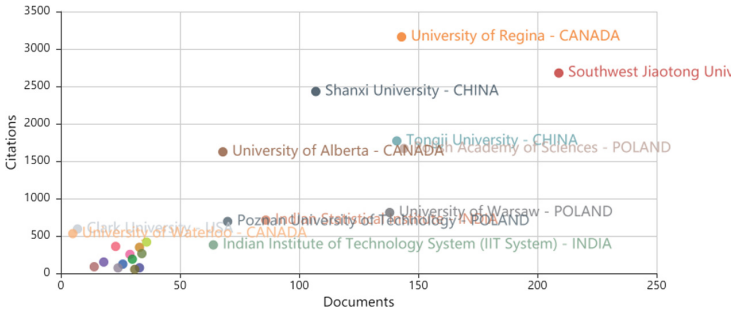

Fig. 7. Comparation in the number of documents and citations of the top institutes.

The main influential institutes are labeled in Fig. 7. Those organizations with less than 50 documents and less than 500 citations are too close to be labeled on the figure. It can be noticed that Southwest Jiaotong University has more papers than the others, but University of Regina has received more citations than any other institutes. Tongji University is very close to Polish Academy of Sciences both in the number of documents and citations. Poznan University of Technology and Indian Statistical Institute are about the same on citations but have different numbers of documents.

5.3 Top Authors

The cooperation networks of authors with more than 30 papers and 15 citations in the recent decade are shown in Fig. 8. The sizes of the nodes represent the amount of papers the authors have published in the RS area. To highlight some of the most productive authors and to distinguish them from their affiliations, the authors with more than or equal to 50 articles are marked with different colors according to their recent institutes. The other authors are all labeled by '_' in gray.

Min from Southwest Petr University, Liang and Qian both from Shanxi University have the broadest range of cooperation. They all have collaborated with up to 9 scholars in the co-author network. Only two of the top authors are not Chinese, Pedrycz from Univ of Alberta and Slowinski from Poznan Univ Tech. Pedrycz has cooperated much more with Chinese than Slowinski in RS area.

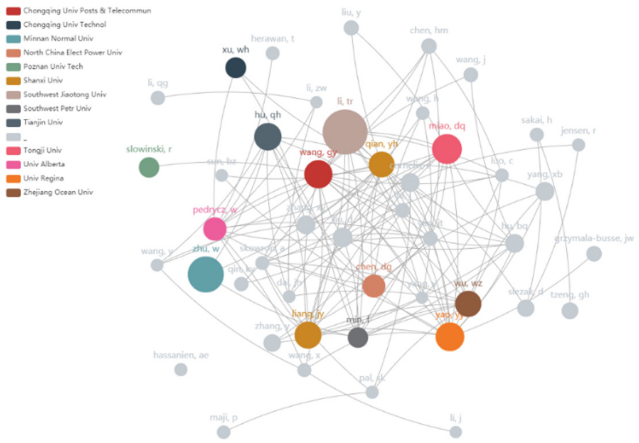

Fig. 8. Cooperation network of authors with more than 30 papers and 15 citations from 2009 to 2018. (Color figure online)

5.4 Chinese Scholars

From the above section, we see that most productive authors come from China. The RS research in China is growing very quickly in recent years. We further analyze the city distribution of Chinese RS community.

Figure 9 shows the main cities of RS researches distributed in China. The number of papers of each city is extracted from address field of bibliographic meta data downloaded from WoS. Full counting is used, i.e. if two cities co-exist in the address of scholars, the amount of papers of each city will increase by 1.

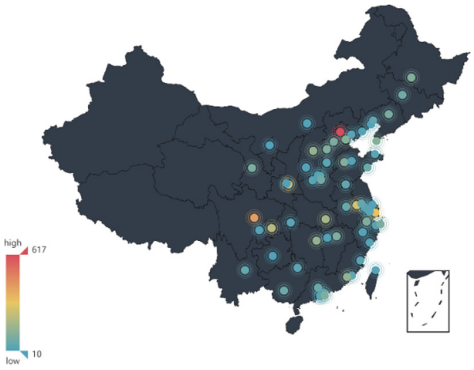

Fig. 9. The distribution of cities in China with more than 10 RS papers.

There are 4295 literatures contributed by Chinese scholars about RS indexed in WoS in recent decade. The scholars are distributed in 190 cities in China. The figure is drawn by pyecharts, and cities with fewer than 10 papers are cut out to make the main

cities noticeable. Among those cities, Beijing has gathered most scholars (617 papers), followed by Chengdu, Xi'an, Shanghai and Nanjing whose numbers of papers are 417, 329, 321 and 283 respectively.

The top Chinese authors are listed in Table 3, and their institutes and their most frequently published journals are shown. These Chinese scholars are also highlighted in Fig. 9 above.

Most of the top authors prefer to publish articles in INFORMATION SCIENCES. They also favour KNOWLEDGE BASED SYSTEMS and INTERNATIONAL JOURNAL OF MACHINE LEARNING AND CYBERNETICS, etc.

Table 3. The top Chinese authors in RS in recent decade.

Author	Papers	Institute	Journal with most publications
LI, TR	110	Southwest Jiaotong Univ	INFORMATION SCIENCES
ZHU, W	88	Minnan Normal Univ	INFORMATION SCIENCES
MIAO, DQ	73	Tongji Univ	INFORMATION SCIENCES/KNOWLEDGE BASED SYSTEMS
WANG, GY	69	Chongqing Univ Posts & Telecommun	INFORMATION SCIENCES
HU, QH	67	Tianjin Univ	INFORMATION SCIENCES
LIANG, JY	66	Shanxi Univ	KNOWLEDGE BASED SYSTEMS
WU, WZ	64	Zhejiang Ocean Univ	INFORMATION SCIENCES
QIAN, YH	63	Shanxi Univ	INFORMATION SCIENCES
CHEN, DG	56	North China Elect Power Univ	INFORMATION SCIENCES/IEEE TRANSACTIONS ON FUZZY SYSTEMS
XU, WH	51	Chongqing Univ Technol	INTERNATIONAL JOURNAL OF MACHINE LEARNING AND CYBERNETICS
MIN, F	50	Southwest Petr Univ	INFORMATION SCIENCES

6 Conclusion and Discussion

This paper provides the comprehensive analysis of research landscape on research of rough sets. We use WoS databases and provide the overview of RS by conducting the bibliometric analysis of 11833 papers published from 1982 to 2018. First, from the distribution of publication, we identify the main development stages over the period The timespan of the science map covers the years from 2009 to 2018 which allows us to identify key points of RS research in recent years. We find some research areas citing

RS are broadening. Second, we identify the main journals and conferences as well as their changes over the last two decades. The third part is the analysis of research collaborations at different granularity of authorship, including the international collaboration, the research performance of top organizations in different countries, the cooperation network of authors, the distribution of cities in China and the top Chinese scholars.

We apply different approaches to visualize data in form of different illustrative graphs to make our analysis easy to read and understand. The results of the study can benefit the researchers who are ready to dive into RS research, as well as those who have launched the relevant investigation.

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