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Research on the cross-citation relationship of core authors in scientometrics

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Abstract Generally speaking, citation relationship among authors can be divided into 3 types: co-citation, coupling and cross-citation. Since author co-citation analysis was first introduced in 1982, it has been widely applied to study discipline structure, research state and research trends. Afterwards, conception of author bibliographic-coupling analysis was put forward and related empirical studies provided a method for mapping active authors in a research field for a more realistic picture of the current state of its research activities. Additionally, if one of author A's papers has a citation from one of author B's, there is cross-citation relationship between A and B. However, studies based on author cross-citation relationship mainly describe citation behaviors themselves using citation identity and citation image; they rarely involve any implicit knowledge communication, author research correlation or discovering academic communities. Author cross-citation analysis infers to both citing and cited phenomenon, which can be roughly correspond to citation identity and citation image. The study will further explore the author cross-citation relationship with core authors in scientometrics field as study object in order to provide reference for development of scientometrics field and in-depth application of citation analysis.

Keywords Scientometrics · Author cross-citation · Knowledge communication · Academic community

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Introduction

Citation analysis as a mature quantitative research method in bibliometrics and scientometrics has been applied to many disciplines at home and abroad, especially in describing evolution of disciplines, evaluating and predicting scientific developing trend. One key function of citation analysis is to discover academic communities according to authors' citation behaviors. It mainly covers 3 types of analysis: author co-citation, author coupling and author cross-citation. Author co-citation analysis (ACA) has formed a relatively steady research pattern (McCain 1990) as the mainstream approach to discover academic communities and explore knowledge structure and has yielded influence on many fields. However, author coupling relationship didn't get much attention and application from informetrics scientists for a long period until it's recently put forward and empirically studied by Zhao and Strotmann (2008b), and they named it author bibliographic-coupling analysis (ABCA). Bibliographic coupling is a term made popular by Kessler (1963). A coupling unit between two documents is an item of reference used by these two documents, so as to the coupling unit between two authors in ABCA, i.e., an item of reference used by these two authors' respective papers. The coupling frequency between two documents is fixed once these two documents have been published, and therefore does not readily support the study of changes in research fields over time (Small 1973). Author-aggregated bibliographic-coupling analysis, however, circumvents this problem because the bibliographic-coupling frequency between two authors (i.e., between their oeuvres) does continue to evolve as long as at least one of them continues to publish. In addition, D. Zhao found author coupling can help identify scholars' study interests and detect current intelligence structure of some specific discipline, which is a good complement for author co-citation analysis. A comparative analysis on author citation phenomenon in scientometrics field had been conducted using author co-citation analysis and author coupling analysis respectively before, successfully discovering academic communities with high impact or activity in the field (Wang 2010). Research about author cross-citation can be traced back to occurrence of conceptions like citation identity and citation image. They are corresponding to two independent sides of author cross-citation behavior and can be combined to form a uniform study on cross-citation relationship. Since the notion of citation identity was put forward by White (2001), plenty of scholars have been dedicated to exploring it (Blaise and Debora 2002; White 2004. But a great deal of related studies today are still focused on describing citation behavior itself, for examples, authors' citation preference, citation features and citation background, while rarely discussing implicit aspects behind citation relationship such as knowledge communication and relationship among authors' studies etc. In fact, given author cross-citation relationships, we can construct authors' cross-citation network to obtain a clear "map of knowledge communication" and master the knowledge flow together with communication dynamics. By building up authors' cross-citation relationship and measuring the cross-citation strength, academic communities and discipline structure from a different view could be found out. And that'll be the key value of this study.

Data and methodology

Scientometrics is a peer reviewed journal in the field of scientometrics. It is currently published by Akadémiai Kiadó and Springer Science + Business Media and has appeared continuously since 1978. Scientometrics has reached and maintained a leading role not

only in its immediate field but also in the broader field of Library and Information Science. As the representative communication channel of its field, it reflects the characteristic trends and patterns of the past decades in scientometric research (Schubert 2002), that's why this study uses the journal -like several of its predecessors (Schubert and Maczelka 1993; Schoepflin and Glanzel 2001; Hou et al. 2008) as a representative model of scientometrics research.

This study is based on bibliographic data retrieved from the Web of Science. The data contains all types of documents published in Scientometrics journal from 1978 to 2011. Each document includes author names, title, keywords, abstract, date, type, addresses, and cited references. Author names including the cited authors were normalized because some authors may report their names differently in different papers. We identified each author by his or her surname and first initial only, so as to the cited authors. The retrieval was finally updated on June 3, 2011.

Variety of methods such as bibliometrics method, social network analysis, citation analysis, co-occurrence analysis,clustering analysis and factor analysis are used to find out the cross-citation relationships among core authors in scientometrics filed and further explore the knowledge structure construction of a specific discipline in the perspective of author cross-citation. Theories of bibliometrics are applied throughout this paper, because laws from bibliometrics can help identify the prolific authors, highly-cited and core authors that will be taken as our study objects. Citation analysis is a powerful tool for investigating formal (intellectual) networks but offers only tantalizing glimpses of the associated informal networks (White and Griffith 1981). Social network analysis (SNA) was also proved to be successful in studies of citation relationship research (White and McCain 1998). It can not only assist to deepen the analysis about clustering results of citation network, but also more accurately reveal the scientific structure and its evolution with the network topology characteristics. We will use the method of SNA systematically to analyze cross-citation network among core authors of scientometrics field. UCINET is the main tool used here. VBA program can process author cross-citation data. The software of SPSS will be applied to do factor analysis and Netdraw for visualizing different network structures is used as supplement.

Results and discussion

Basic results

There were 2,989 documents published in Scientometrics journal during 1978–2011, including 2,982 articles with authors, 2,815 articles with references, 2,812 articles with both. There are 35,796 references, i.e., about 14 references per source paper on average. The total number of authors is 2,994 by merging the different signatures of the same authors, including 1,484 first authors. The top 32 prolific authors (publishing 10 or more papers) were shown in Table 1. There are 16,057 cited authors including 60 authors (first author) with cited frequencies more than 100 (see Table 2).

So far, there was no report on any standard for identifying core authors in scientific field. Lotka and Price mainly identified excellent scientists according to number of their published papers during the study on scientists' productivity and activity patterns. Garfield treated those with high cited frequency from SCI as excellent scientists (Qiu 2007). Many other scholars also adopted different approaches to evaluate core authors in information science. Nevertheless, eventually they all considered both number of published papers and

Table 1 The top 32 prolific authors

Author	Articles	Author	Articles	Author	Articles
Schubert A.	56	Gupta B. M.	19	Kostoff R. N.	12
Glanzel W.	54	Lewison G.	19	Pouris A.	12
Braun T.	53	Kretschmer H.	18	Yu G.	12
Egghe L.	47	Moed H. F.	17	Bornmann L.	11
Leydesdorff L.	34	Nederhof A. J.	16	Meyer M.	11
Vinkler P.	30	Burrell Q. L.	15	Nagpaul P. S.	11
Moravcsik M. J.	29	Bar-ilan J.	14	Zitt M.	11
Bonitz M.	22	Garg K. C.	14	Campanario J. M.	10
Rousseau R.	20	Haitun S. D.	14	Todorov R.	10
Small H.	20	Eto H.	13	Wagner-dobler R.	10
Van Raan A. F. J.	20	Abramo G.	12		

Table 2 The 60 most highly cited authors

Author	Frequency	Author	Frequency	Author	Frequency
Garfield E.	1,198	Price D. D.	200	Lewison G.	130
Glanzel W.	807	Cronin B.	196	Haitun S. D.	129
Braun T.	634	Moravcsik M. J.	190	Bornmann L.	129
Egghe L.	615	Martin B. R.	186	Macroberts M. H.	125
Leydesdorff L.	612	Frame J. D.	175	Etzkowitz H.	125
Narin F.	578	Katz J. S.	174	Seglen P. O.	123
Schubert A.	533	Cole S.	173	Zuckerman H.	122
Moed H. F.	505	Kostoff R. N.	170	Carpenter M. P.	121
Price D. J. D.	472	Burrell Q. L.	169	Bonitz M.	119
Small H.	432	Nalimov V. V.	155	Pavitt K.	112
Van Raan A. F. J.	363	Beaver D. D.	154	Schmoch U.	111
Merton R. K.	289	Hirsch J. E.	153	Hicks D.	111
Vinkler P.	271	Brookes B. C.	151	Irvine J.	110
Rousseau R.	268	Arunachalam S.	150	Bordons M.	110
Callon M.	232	Grupp H.	148	Lotka A. J.	109
Meyer M.	223	Zitt M.	146	Crane D.	106
Nederhof A. J.	212	Luukkonen T.	143	Ingwersen P.	105
Vlachy J.	208	Tijssen R. J. W.	141	Bar-ilan J.	104
White H. D.	207	McCain K. W.	136	Noyons E. C. M.	101
Thelwall M.	207	Cole J. R.	132	Newman M. E. J.	100

cited frequency. Therefore, the study identified 94 authors who have published 5 or more papers and simultaneously cited frequency over 10 as core authors. Statistical work shows that top 32 prolific authors (cited more than 40 times) are all among the 94 core authors. Authors like Schubert A., Glanzel W., Braun T., Egghe L., Leydesdorff L. are both most prolific and highly cited. However, although Garfield E. is highly cited, he is not among the prolific authors due to the limitation of data source and statistical coverage and some other

objective reasons. In addition, there are some authors who published many papers but were barely cited or been cited frequently but few papers published. As a result, they are not counted in core author group. For example, Rey-rocha J. and Van Leeuwen T. N. as first author both published over 5 papers but their cited frequency is 0. Authors like Callon M., White H. D. and Price D. D. have cited frequency over 200, but they have less than 5 papers in Scientometrics journal, as a result they are also excluded from core author group. They are listed in the Online Supplement. In the future study, we will further improve the data source and statistical coverage to obtain a more objective analysis on core authors in the field. In order to get insight of authors' cross-citation relationship in scientometrics field and further discover their knowledge flow, mutual influence and correlation of corresponding researches, we will select the above highly productive authors, highly cited authors and core authors to analyze the interactive cross-citation relationship.

Analysis on highly productive authors' cross-citation relationship

If one of author A's papers has a citation from one of author B's, there is cross-citation relationship between A and B. The frequency of A and B's relation can be used to measure cross-citation strength between them. By studying highly productive authors' cross-citation relationship, similarity of different authors' research directions and research coherence of one single author can be discovered.

Cross-citation relationship among highly productive authors was built up with self-coded VBA program and further transformed into an original cross-citation matrix as in Table 3. In the table, rows represent citing authors and columns represent cited authors, the diagonal represents self-citation frequency. From citation frequency analysis, self-citation frequency is the highest among all cross-citation relationships, which to some extent shows that authors have greatest influence on their own future studies. Difference also exists between citing frequency and cited frequency. Glanzel W.'s citing frequency is the highest (182 times), he is followed by Schubert A. (127 times) (here, the numbers are obtained by counting horizontally from the whole table). It's highly related to their high paper productivity. Among cross-citation relationships of highly productive authors, Schubert A. and Braun T. are cited the most times, 222 and 202 respectively (here, the numbers are obtained by counting vertically from the whole table). And Glanzel W. ranked in the third place. These above researchers led the research frontier of scientometrics field. Studies of many other scholars are somehow extension or improvement of their work and thus form some similarity with theirs. Sum of one author's citing and cited times is his whole cross-citation relationship in the dataset. Statistical result shows that the first 4 authors on paper productivity rank have strongest cross-citation relationship with the other authors. They are Schubert A., Glanzel W., Braun T. and Egghe L.

Statistical work on number of citing authors shows that Schubert A., Glanzel W., Leydersdorff L., Zitt M., Vinkler P., Van Raan A. F. J. and Eto H. have the most citing authors corresponding to over 15 for each one. While from view of number of cited authors, Schubert A., Glanzel W., Braun T., Egghe L., Leydesdorff L., Moravcsik M. J., Rosseau R., Small H., Van Raan A. F. J, Moed H. F. C and Nederhof A. J. have the most cited authors (over 15). The results also respectively reflect the view of citation identity and citation image with the former one showing the influence the others have on them and the latter one delineating the other way around. So authors in the above two groups either have been greatly influenced or have yielded great influence. And both situations have clearer reflection among highly productive authors. Further statistical work shows that authors whom they have influenced are more centralized than authors who have influenced

Table 3 Original cross-citation matrix of highly productive authors (part of it)

	Schubert A.	Glanzel W.	Braun T.	Egghe L.	Leydesdorff L.	Vinkler P.	Moravcsik M. J.	Bonitz M.	Rousseau R.	Small H.
Schubert A.	48	14	42	1	5	3	10	7	1	5
Glanzel W.	64	171	28	12	5	2	0	0	9	5
Braun T.	46	12	136	0	2	0	3	2	0	0
Egghe L.	6	20	7	196	0	0	0	2	34	1
Leydesdorff L.	1	3	20	1	193	1	2	0	4	22
Vinkler P.	23	10	22	8	2	128	7	3	1	1
Moravcsik M. J.	0	0	2	0	0	0	10	0	0	0
Bonitz M.	13	3	11	2	1	1	10	56	0	2
Rousseau R.	2	3	0	26	3	3	0	1	31	2
Small H.	0	1	0	0	1	0	6	0	0	57

them. Some authors have no influence on others except themselves. This may be partly caused by the delay of citation. In other words, scholars' influence comes later than their study activity. Moreover, it's noticed that some scholars may frequently cite another author's literature but not the other way around. For example Vinkler P. cited Braun T.'s literature 22 times in total, but Braun T. cited no Vinkler P.'s literature at all. This may be caused by the similarity in their research areas and different time when they first enter the areas (Braun entered earlier than Vinkler). Thus Braun T. yielded great impact on Vinkler P. while Vinkler P.'s impact on Braun T. is not strong so much. Besides, Braun and coworkers have no common publications with Vinkler. So, the research similarity and citation relationship between them should attract more attention.

With further analysis over the cross-citation authors, it's found that Glanzel W. cited Schubert A. the most times among the cross-citation relationship formed by 32 highly productive authors. Braun T. and Schubert A. ranked in the second position. Table 4 lists out pairs of cross-citation authors with frequency over 20. We can see from the table that core authors like Schubert A., Glanzel W., Braun T., Egghe L., Burrell Q. L., Rousseau R., Moed H. F., Vinkler P., Leydesdorff L. and Nederhof A. J. share relatively big similarity and the first four authors are key connective nodes. But we found collaborative relationship among Schubert A., Glanzel W. and Braun T. or Egghe L. and Rousseau R. or Nederhof A. J. and Moed H. F. Their citation relationship thus can be treated as coauthor-citation, which in this circumstance is likeas similar as self-citation. The existence of such kind of citation relationship may hinder us from discovering the real cross citation relationship. To solve this problem, we figure out coauthors and eliminate cross-citation relationship among coauthors to obtain the real cross citations of prolific authors. Result shows that the strongest cross-citation relationships lie in Egghe L. and Burrell Q. L. or Glanzel W. or Vinkler P. and Schubert A. or Braun T. or Leydesdorff L. and Small H. or Braun T. These may be the key relationships that we are about to mine. Some authors may have not that high general cross-citation strength, but they are strongly cross-cited with one individual author. The phenomenon shall not be neglected, for it may be an important point of the study. For example the recent winners of the highest prize in scientometrics field-2009 Derek John De Solla Price Medal, Vinkler P. and Zitt M. They were chemist and management scientist respectively in their earlier career and achieved great accomplishments in

Table 4 Pairs of highly cross-cited authors

Citing author	Cited author	Frequency	Co-authors
Glanzel W.	Schubert A.	64	Yes
Braun T.	Schubert A.	46	Yes
Schubert A.	Braun T.	42	Yes
Egghe L.	Rousseau R.	34	Yes
Glanzel W.	Braun T.	28	Yes
Burrell Q. L.	Egghe L.	26	No
Rousseau R.	Egghe L.	26	Yes
Nederhof A. J.	Moed H. F.	26	Yes
Vinkler P.	Schubert A.	23	No
Vinkler P.	Braun T.	22	No
Leydesdorff L.	Small H.	22	No
Egghe L.	Glanzel W.	20	No
Leydesdorff L.	Braun T.	20	No

hot topics including citation analysis and evaluating methods. Vinkler P. has many personal published papers in scientometrics filed and he mainly cited Schubert A., Glanzel W., Braun T., Moed H. F. and Egghe L. Zitt M. doesn't have many published papers where he was the first author, but from his 14 papers, we can see his major citation objects are also Schubert A., Leydesdorff L., Small H. and Moed H. And these people happened to be Price Medal winners who are high-level scholars. Meanwhile, with these new comers entering into the field and development of their academic level, seniors (like Schubert A, Glanzel W., Moed H. F. etc.) in the field begin to notice them and some cross-citation phenomenon eventually emerges. Similarity in their research areas to some extent appears and they lead the development of scientometrics field together.

Netdraw software is used to visualize the cross-citation relationship among the above highly productive authors (as in Fig. 1). Round nodes in the Fig. 1 represent number of authors' published papers. Size of ties represents the cross-citation strength between each pair of authors. Combined with clustering results from SPSS, Schubert A., Braun T. and Glanzel W. were found to have the strongest relationship and many other authors are connected by them. And they have the highest degree centrality. Rousseau and Egghe L., Moed H. F. and Van Raan A. F. J also have pretty strong relationship, which indicates their studies are highly related. Further centrality analysis on the cross-citation network shows that top 11 authors in degree centrality are all Price Medal winners. Their betweenness centrality is almost the highest as well. This is in accordance with the principle that "the stronger you are, the stronger you will be". This is also consistent with the view that White put forward about citation identity which says "Recitation by one respected figure is good; recitation by many respected figures is better; recitation by hundreds of respected figures is world fame" (White 2001). Besides, it's important that we notice that new comers of scientometrics field have more or less cross-citation relationship with those high-level senior scholars, for example, previously mentioned Vinkler P., Zitt M., Garg K. C. and Burrell Q. L. The process of establishing citation relationship with seniors also sees their way to success. Meanwhile, from Fig. 1, we can see that the above seniors are positioned

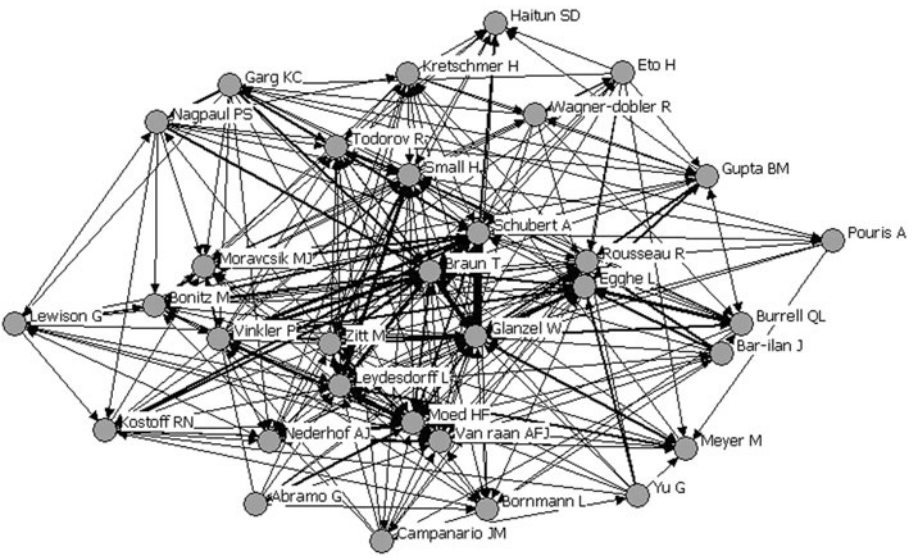

Fig. 1 Cross-citation network of highly productive authors

in center of the network and this is also where the center of scientometrics field lies. Additionally, some other highly productive authors are positioned around. They are following the research trend and simultaneously extending research span in the field.

There is also limitation from individual cross-citation frequency, besides the influence of coauthor relationship on authors' real citation relationship. So we introduce the cross-citation density to more properly reflect cross-citation strength. We get Table 5 (in the table bold numbers indicate coauthor or self-citation relationship, Table 8 is the same) by eliminating authors' self-citation, coauthor citation and normalizing the original matrix according to the total number of cited authors based on Table 3. Among the newly constructed matrix, we find that the strongest citation relationship is from Burrell Q. L. to Egghe L., the second strongest is from Yu G. to Egghe L. From the perspective of mutual cross-citation, the above two pairs of authors, Yu G. and Bonitz M., Schubert A. or Burrell Q. and Glanzel W. have relatively intimate relationship. Among this prolific author group, Zitt M. has the highest citing frequency. He is followed by Bonitz M. and Burrell Q. L. Braun T. has the highest cited frequency. He is followed by Schubert A. and Egghe L. Moreover, network structure analysis on the matrix shows that Braun T's centrality degree has become the highest, he is followed by Schubert A. Glanzel W., however, is behind authors like Egghe L., Moed H. F., Small H., Zitt M., and ranks the seventh. His ranking in betweenness degree has also dropped (from the fifth to the tenth). This is probably because Glanzel W. has many coauthors in the prolific author group and these authors happen to be his major cross-citation authors. Besides, both Schubert A. and Leydesdorff L.'s ranking in centrality measure have dropped which is related to their large number of citing authors. Generally speaking, the essential core–edge structure of authors stays unchanged by coauthor relationship eliminated and normalization. The true citation relationships among authors are revealed, this is of great help to scholars who try to build up relationship mining model in the future.

A Cross-citation analysis between highly productive authors and highly cited authors

Previous analysis mainly reveals research structure of one-mode network formed by highly productive authors. Now we will analyze two-mode network built up upon citation relationship between highly productive authors and highly cited authors in order to find out synergetic relationship between highly productive authors and highly impactive authors and further discover common points of their study areas. Here we select the above 32 highly productive authors and 60 highly cited authors to analyze.

First of all original citation matrix of them is built, as shown in Table 6. In the table, rows represent highly productive authors, columns represent highly cited authors. Citing direction is from row to column. Some authors could be both highly productive authors and highly cited authors. The overlapped data then is self-citation frequency. Through the analysis between two groups of authors, it's found that Schubert A., Glanzel W., Egghe L., Leydesdorff L. and Vinkler P. cited those highly cited authors the most times (each of them over 300 times). When self-citation is not taken into consideration, Schubert A. has got the highest citing frequency and "Father of SCI" Garfield E. has got the highest cited frequency. Glanzel W., the coeditor of Scientometrics journal, ranks both in the second place in citing and cited frequency. This again verified their authoritative position in scientometrics field. After the elimination of coauthor citations, there is only Vinkler P. whose citing frequency is over 300 (Vinkler P.'s papers on Scientometrics journal are all finished alone with no coauthor) Schubert A. and Leydesdorff L. rank second and third, respectively, and Glanzel W. ranks the fifth. In cited frequency counting, Garfield E. still ranks

Table 5 Normalized cross-citation matrix of highly productive authors (part of it)

	Schubert A.	Glanzel W.	Braun T.	Egghe L.	Leydesdorff L.	Vinkler P.	Moravcsik M. J.	Bonitz M.	Rousseau R.	Small H.
Schubert A.	**0**	**0**	**0**	0.0007	0.0033	0.002	0.0066	0.0046	0.0007	0.0033
Glanzel W.	**0**	**0**	**0**	0.018	0.0075	0.003	0	0	**0**	0.0075
Braun T.	**0**	**0**	**0**	0	0.0054	0	0.008	0.0054	0	0
Egghe L.	0.0094	0.0314	0.011	**0**	0	0	0	0.0031	**0**	0.0016
Leydesdorff L.	0.0009	0.0028	0.0186	0.0009	**0**	0.0009	0.0019	0	0.0037	0.0204
Vinkler P.	0.0424	0.0185	0.0406	0.0148	0.0037	**0**	0.0129	0.0055	0.0018	0.0018
Moravcsik M. J.	0	0	0.0357	0	0	0	**0**	0	0	0
Bonitz M.	0.057	0.0132	0.0482	0.0088	0.0044	0.0044	0.0439	**0**	0	0.0088
Rousseau R.	0.0076	**0**	0	**0**	0.0115	0.0115	0	0.0038	**0**	0.0076
Small H.	0	0.003	0	0	0.003	0	0.0182	0	0	**0**

Table 6 Original cross-citation matrix between highly productive authors and highly cited authors (part of it)

	Garfield E.	Glanzel W.	Braun T.	Egghe L.	Leydesdorff L.	Narin F.	Schubert A.	Moed H. F.	Price D. J. D.	Small H.
Schubert A.	25	14	42	1	5	12	48	6	4	5
Glanzel W.	11	171	28	12	5	10	64	13	6	5
Braun T.	11	12	136	0	2	9	46	4	5	0
Egghe L.	4	20	7	196	0	0	6	3	5	1
Leydesdorff L.	14	3	20	1	193	20	1	9	12	22
Vinkler P.	27	10	22	8	2	10	23	13	3	1
Moravcsik M. J.	0	0	2	0	0	0	0	0	2	0
Bonitz M.	19	3	11	2	1	3	13	0	4	2
Rousseau R.	6	3	0	26	3	0	2	2	2	2
Small H.	19	1	0	0	1	4	0	0	6	57

the first. He is followed by Vinkler P. and Narin F. This is mainly because they have no coauthor in these two groups. But Glanzel W. has 8 coauthors and the elimination of cross citations will certainly cause the drop of his ranking.

Previously we analyzed citing and cited relationship among highly productive authors. Here we will conduct a similar analysis on highly productive authors and highly cited authors to obtain some insight. From view of the number of citing authors, Schubert A., Leydesdorff L. and Vinkler P. have the most authors (citing more than 40 authors). They are followed by Glanzel W., Zitt M., Van Raan A. F. J., Moed H. F., Braun T. and Nederhof S. J. (citing more than 30 authors). They are greatly influenced by highly cited authors and meanwhile they belong to highly cited author group themselves. From view of the number of cited authors, Garfield E. and Price D. J. D have the most cited authors (cited by more than 25 authors). It's known that they created classical theories and methodologies that are continually cited by successors in scientometrics field. Although Price passed away forever and Garfield is getting old, which make them no longer to be statistical object of highly cited authors, their influence keeps on. They are followed by Glanzel W., Braun T., Schubert A., Van Raan A. F. J. and Narin F. etc., whose impact is also fairly high. Similar to previous statistical results of highly productive authors' cross-citation relationship, here authors (the influencing author group) who are cited by the highly productive authors are relatively scattered, while authors (the influenced author group) who cite the highly cited authors are rather centralized. Several authors with rather high total cited frequency yielded impact on only 3–5 highly productive authors and that even counts themselves (for example Bar-ilan J., Newman M. E. J. and so on). This reflects that although coupling of citing authors is not created on purpose, it's a general result of authors' common citing preference, citing willing and citing motivation during their studies. Most scholars are likely to cite those high-level authors or authors in the similar research field or authors they have close social relationship with. This is consistent with conclusions from citation identity and citation image (Blaise and Debora 2002).

Combined with previous analysis on highly productive authors' cross-citation matrix, it's easy to see that there seems to be some correlation between citing frequency and number of published papers. In the next step, we will continue to verify this correlation with SPSS, as in Table 7. We found a positive and significant correlation between output of authors and citing frequencies after investigating the correlation between output and three aspects of citing frequencies (refer to citation relationship among highly productive authors, citation relationship between highly productive authors and highly cited authors and Self-Citing), which indicated that most of the prolific authors are also active in citing

Table 7 Correlation between output and citing frequencies

Pearson correlation	Output	Citings (1)	Citings (2)	Self-citings
Output	1	0.799[a]	0.703[a]	0.703[a]
Citings (1)	0.799[a]	1	0.941[a]	0.941[a]
Citings (2)	0.703[a]	0.941[a]	1	1
Self-citings	0.703[a]	0.941[a]	1	1

[a] Correlation is significant at the 0.01 level (2-tailed)

(1) Represents relationship among highly productive authors; (2) Represents citation relationship between highly productive authors and highly cited authors

behaviors of the scientometrics field. Citation behaviors are particularly frequent between highly influential authors and highly active authors.

The construction of authors' citation relationship somehow reflects mutual knowledge communication. We proceed to draw citation relationship between highly productive and highly cited authors into network map (as in Fig. 2). It's generally found that citation relationship runs from left to right while knowledge flow is just on the contrary from right to left (from square nodes to round nodes). And citation frequency has decided the degree of knowledge flow. Authors represented by square nodes positioned on the left have gained more cited frequency and their knowledge output is relatively more. Authors represented by round nodes positioned on the right have more citing frequency and correspondingly more knowledge flow-in. Meanwhile round nodes and square nodes are partially intersected. Some authors have both knowledge flow-out and knowledge flow-in and thus are in the most key position on the network map, which are the core and linkage of the entire scientometrics field as well. It's their great work that has continually led the other scholars rapidly develop the field.

Similarly, self-citation and coauthor citation from the highly productive-highly cited author cross-citation matrix was eliminated. After normalization we get Table 8. Similar to previous analysis, authors like Vinkler P., Schubert A., Leydesdorff L., Glanzel W. have the highest citing authors, so they are no longer the focus of highly citing group. They are replaced by authors like Bonitz M. and Burrell Q. L. This verified their active activity. In cited area, besides Garfield E.'s firm status, authors like Braun T., Narin F. and Schubert A. also show great cited frequency which reflects their prominent contribution and high impact to some extent.

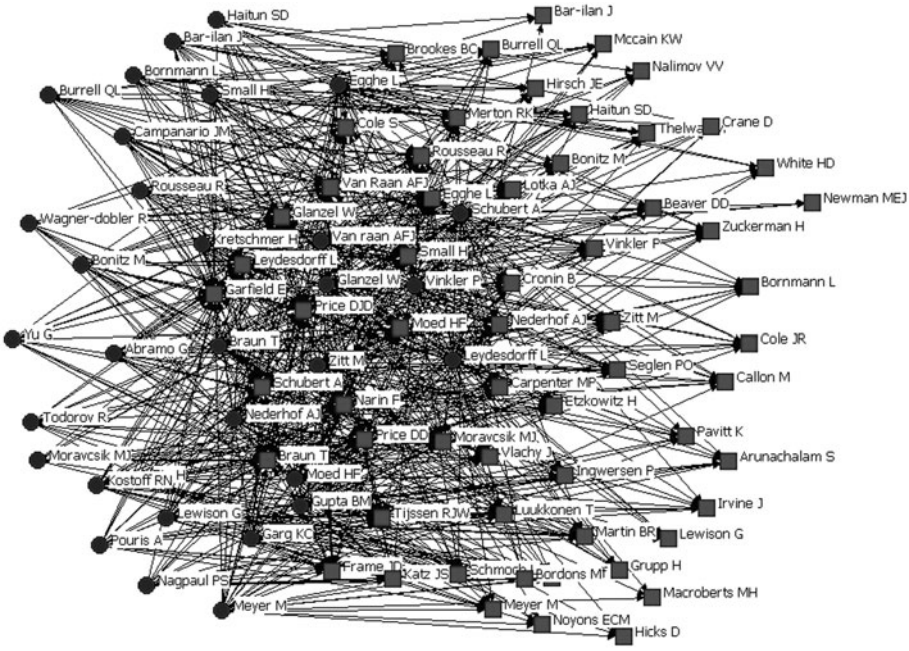

Fig. 2 Citation relationship network between highly productive authors and highly cited authors. *Round nodes* represent highly productive authors; square nodes represent highly cited authors

Table 8 Normalized cross-citation matrix between highly productive authors and highly cited authors (part of it)

	Garfield E.	Glanzel W.	Braun T.	Egghe L.	Leydesdorff L.	Narin F.	Schubert A.	Moed H. F.	Price D. J. D.	Small H.
Schubert A.	0.0165	**0**	**0**	0.0007	0.0033	0.0079	**0**	0.0039	0.0026	0.0033
Glanzel W.	0.0165	**0**	**0**	0.018	0.0075	0.015	**0**	**0**	0.009	0.0075
Braun T.	0.0295	**0**	**0**	0	0.0054	0.0241	**0**	0.0107	0.0134	0
Egghe L.	0.0063	0.0314	0.011	**0**	0	0	0.0094	0.0047	0.0078	0.0016
Leydesdorff L.	0.013	0.0028	0.0186	0.0009	**0**	0.0186	0.0009	0.0084	0.0112	0.0204
Vinkler P.	0.0498	0.0185	0.0406	0.0148	0.0037	0.0185	0.0424	0.024	0.0055	0.0018
Moravcsik M. J.	0	0	0.0357	0	0	0	0	0	0.0357	0
Bonitz M.	0.0833	0.0132	0.0482	0.0088	0.0044	0.0132	0.057	0	0.0175	0.0088
Rousseau R.	0.0229	**0**	0	**0**	0.0115	0	0.0076	0.0076	0.0076	0.0076
Small H.	**0**	0.003	0	0	0.003	0.0121	0	0	0.0182	**0**

Analysis on core authors' cross-citation relationship

Previous part has shown citation relationship in detail among highly productive authors and between highly productive and highly cited authors. Now we will classify authors according to research correlation established upon cross-citation relationship in order to help scholars summarize research patterns, discover research communities, find out hot topics and develop their disciplines in the future.

Here we select the previously mentioned 94 first authors with published papers over 5 and cited frequency over 10 as core authors to do cross-citation relationship analysis. To begin with, original cross-citation matrix among core authors is built (as in Table 9). This part of research is aimed to propose a new method for analyzing author cross-citation relationship that is different from coauthor analysis and author co-citation analysis, in order to recognize discipline structure and identify scholar communities. So coauthor situation is not excluded during the core author cross-citation matrix construction and the classification analysis based on the matrix. For comparison analysis with the two mature methods, traditional analyzing procedures will be applied using original cross-citation matrix for the following analysis (Self-citation and coauthor citation eliminated, and normalization see "Appendix").

Factor analysis is conducted on the above cross-citation matrix. 14 factors having explained 86.026% of the total variance were extracted by principal component analysis (PCA) and oblique rotation (SPSS Oblimin). An oblique rotation can produce two distinctive matrices: structure matrix and pattern matrix. Loadings in the pattern matrix represent the unique contribution of individual authors (variables) to specialties (factors), whereas loadings in the structure matrix, which represent simple correlations between variables and factors, are determined both by an author's unique contribution to each factor and by the correlation among factors (Hair et al. 1998). Therefore, we will select the structure matrix to do further analysis. We visualized the factor loading matrix as two-dimensional map using the technique introduced by Zhao and Strotmann (2008a) to aid interpretation. On the map (i.e., Fig. 3), authors are represented by square nodes and factors by round nodes. The size of a factor node corresponds to the sum of the loadings on this factor by all authors who load sufficiently on it (i.e., with a value of 0.1 or higher in this case). The width of a line that connects an author with a factor is proportional to the loading of this author on this factor. The gray level of an author node indicates the number of factors that this author loads on with a value of at least 0.1 for each one; the deeper the colour is, the more the loading factors are. Since every loading of factor 9 is below 0.1, it's not shown on the Fig. 3. Figure 3 shows that Thelwall M., Kostoff R. N., Bornmann L. and Bar-ilan J. are becoming isolated nodes that don't belong to any factor based on the threshold value of the loading.

From statistical work on titles and keywords of authors' published papers in every factor, we can find out research area that each factor represents. Although there are 13 factors in the Fig. 3, some factors are strongly related and indivisible due to the nature of cross-citation relationship that it's not as clear as author co-citation analysis in classifying authors. For example, factor 11, factor 13 and factor 14 are all tiny branches and have mutual intimate relationship. In addition, factor 8 and factor 12 are not independent enough and depend on the other big factors. Factor 10 is even smaller with only 3 authors having load on it and each one below 0.2. Its total value can nearly be neglected. To sum up, we extracted factors with the first factor loading and classified the above authors into 8 classes according to their cross-citation relationship, as shown in Table 10.

Table 9 Cross-citation matrix among core authors (part of it)

	Garfield E.	Glanzel W.	Braun T.	Egghe L.	Leydesdorff L.	Narin F.	Schubert A.	Moed H. F.	Small H.	Van Raan A. F. J.
Garfield E.	41	0	1	0	0	1	0	0	1	0
Glanzel W.	11	171	28	12	5	10	64	13	5	6
Braun T.	11	12	136	0	2	9	46	4	0	2
Egghe L.	4	20	7	196	0	0	6	3	1	5
Leydesdorff L.	14	3	20	1	193	20	1	9	22	7
Narin F.	1	0	0	0	0	23	0	0	2	0
Schubert A.	25	14	42	1	5	12	48	6	5	3
Moed H. F.	11	4	8	1	0	5	9	35	3	6
Small H.	19	1	0	0	1	4	0	0	57	1
Van Raan A. F. J.	1	3	3	5	2	5	0	19	6	34

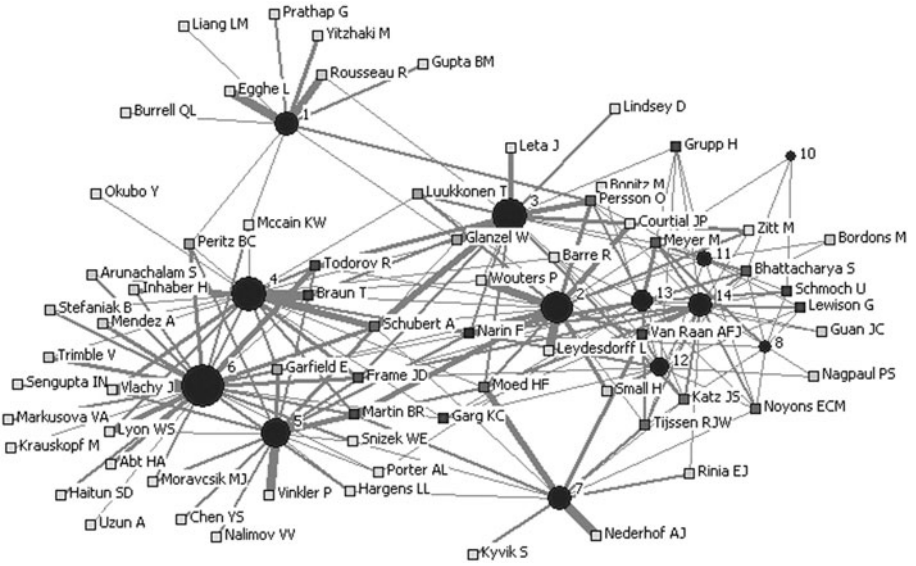

Fig. 3 Result graph of factor analysis on core authors' cross-citation relationship. *Round nodes* represent authors; *square nodes* represent factors

Table 10 Factors and their labels

Num.	Label	Size	Highest loading	Core author
1	Informetrics and Bibliometrics	11	0.983089	Egghe L., Rousseau R.
2	Dynamics of Science and Technology	17	0.988559	Leydesdorff L., Wouters P.
3	Citation and Science Communication	19	0.978873	Glanzel W., Schubert A.
4	Scientometrics Indicators and Basic Research Assessment	24	0.964875	Braun T., Schubert A.
5	Scientific Indicators and Evaluation of Research Performance	19	0.9766	Vinkler P., Martin B. R.
6	Application Research of Scientometrics	27	0.952885	Vlachy J., Lyon W. S.
7	Bibliometrics Indicators and Mapping of Science	12	0.96133	Nederhof A. J., Moed H. F.
8	Patent-metrics and Linkage between Science and Technology	15	0.460493	Meyer M., Narin F.

The size of a factor reflects the number of authors who load on it, and thus indicates the activity level of each specialty in the scientometrics field; the highest load in each factor indicates how distinctive the corresponding specialty is within the scientometrics field; the core author indicates the most influential person in the relevant fields. Informetrics and Bibliometrics in factor 1 are mainly represented by Egghe L. and Rousseau R. This class mainly focuses on basic theories and methods of Informetrics and Bibliometrics. Dynamics of Science and Technology in factor 2 are mainly represented by Leydesdorff L. and

Wouters P. This filed has some relationship with factor 8, Patent-metrics and Linkage between Science and Technology and is also involved in factor 13, factor 14, factors 11 and factor 8. They all belong to new research areas in scientometrics field and mainly discuss about relationship between science and technology and their applications. Factor 3 represents Citation and Science Communication with key authors such as Glanzel W. and Schubert A. This is also the most active and impactive research frontier in scientometrics field. Scientometrics Indicators and Basic Research Assessment indicated by factor 4 is related and complementary with factor 5, which is Scientific Indicators and Evaluation of Research Performance. Both of them emphasize a lot in theories behind scientific indicators and in application of evaluation. The difference lies in that the former one emphasizes more on basic research evaluation on authors and journals etc. while the latter one on international and interdisciplinary scientific achievement evaluation. The former one is represented by Braun T. and Schubert A. while the latter one by Vinkler P. and Martin B. R. etc. The factor that covers the most authors and has the largest load value is factor 6, namely Application Research of Scientometrics. It's a big application research area whose representative authors including Vlachy J. and Lyon W. S. etc. Factor 7 represents Bibliometrics Indicators and Mapping of Science of which the typical authors including Nederhof A. J. and Moed H. F. They mainly study theory and application of bibliometrics indicators and scientific knowledge map that functions as crucial support for citation analysis and co-word analysis.

Conclusions

The study selected 32 highly productive authors, 62 highly cited authors and 94 core authors considering both number of publication and citation in scientometrics field for mutual cross-citation analysis and finally drew network map comprising each of these 3 groups. An in-depth exploration into relationship network of these 3 groups combining citation analysis, co-occurrence analysis, social network analysis and factor analysis brings the following conclusions:

(1) Studies on highly productive authors can help find similarities of different authors' research areas and research consistency of individuals. From analysis on highly productive authors' cross-citation frequency, self-citation frequency was found to be the highest among cross-citation relationship. This partially means that authors receive greatest influence in the future study from themselves. There also exists difference between citing frequency and cited frequency. Glanzel W. and Schubert A. have the highest citing frequency while Schubert A. and Braun T. have the highest cited frequency. They are currently the most active authors and leading the frontier of scientometrics field together. From accumulated bidirectional strength of cross-citation we can see that the top four prolific authors are also the most related with the other authors. Thus we speculate that strength of cross-citation may be also an important feature of authors' activity.

Statistical work on cross-citation number of authors can correspond to citation identity and citation image. The former one depicts the influence on a scientist from the others and himself, while the latter one delineating the other way around. Impacting authors in the group are more centralized than the influenced authors from statistic work analyses. Some authors have hardly yielded any influence on the others except on their own studies. This is more or less caused by the delay of citations. In other words, scholars' influence comes later than their activity. Moreover, we notice that some authors may frequently cite another

author's papers while not the other way around. This may be decided by authors' entering time in the specific area and their influence.

Analysis on cross-citation authors reveals similarity and homogeneity of different authors' studies. Statistic shows that some winners of the highest reward, the Price Medal, such as Schubert A., Glanzel W., Braun T., Egghe L., Leydesdorff L. and Moed H., usually have the strongest mutual cross-citation relationship or relationship with the other authors. They are the key connective nodes of the whole cross-citation network and also share relatively big similarity. Furthermore, some authors may have no high general cross-citation strength but have rather high cross-citation relationship with some individual author. This is typical feature of study homogeneity. In cross-citation network formed by highly productive authors, senior scholars including Schubert A., Braun T. and Glanzel W. are positioned in the center. Correspondingly, they are also in the center of scientometrics field. Meanwhile their betweenness centrality is almost the highest as well, which is similar to citation identity. Establishment of cross-citation relationship also obeys "the stronger get stronger" principle.

(2) Analysis on two-mode network structure established between highly productive authors and highly cited authors is aimed at discovering the synergetic relationship between highly impactive authors and highly productive authors in order to further explore common points of their studies. By analyzing citation frequency between the two author groups, it's found that authors like Schubert A., Glanzel W. and Egghe L. have cited the most times on highly cited authors. When self-citation is not taken into consideration, Schubert A. has the highest citation frequency, Garfield E has the highest cited frequency and Glanzel W. ranks in the second place in both indicators. Statistical work on number of cross-citation authors demonstrates that scholars including Schubert A., Leydesdorff L. and Vinkler P. have the most citing authors. They are strongly influenced by highly cited authors and belong to highly cited group at the same time. Garfield E. and Price D. J. D are cited by the highest number authors. It's known that they created classical theories and methodologies and tools of scientometrics that are continually cited and admired by the future scholars. The phenomenon of citation scattering and cited concentration is consistent with statistical work on highly productive authors. This in a way demonstrates that although citation authors' coupling (i.e., citation image making) is not intentionally created, it's a combined reflection of common sides of citation preference, citation willing and citation motivation that authors have in their studies. Most scholars may tend to cite those high-level authors or authors that have same research areas or intimate social relationship with them. This is in consistency with conclusions from citation identity and citation image. In addition, correlation analysis shows that most prolific authors are also active in citing behaviors in the field of scientometrics, especially frequently on those highly impactive authors or highly active authors.

The establishment of author citation relationship has partially reflected mutual knowledge flow. The citation relationship between highly productive authors and highly cited authors is further visualized into a network map. In this map, citation relationship is basically from left to right while knowledge flow is on the contrary from right to left. Difference in citation frequency has decided the extent of knowledge flow. The higher the author gets cited, the more knowledge flows out and vice versa. Among knowledge flow-out and knowledge flow-in groups there do existing overlapped authors that have both knowledge flow-out and knowledge flow-in. Most of them are in central positions in the network map which means they are kernel and connective ties in the entire knowledge communications of scientometrics field. It's their positive and active work that has continually led the other scholars boost the rapid development of the area.

(3) In addition, we find that collaborative relationship may influence their mutual citation relationship. Citations among collaborative authors can be treated as coauthor citations, which in the circumstance is like self-citation. The existence of these citation relationships may hinder us from discovering the real cross citation relationship. Besides, cross-citation frequency among authors is related to their total number of citing authors rather than being independent from each other. To solve this problem, we introduced cross-citation density to more properly reflect the cross-citation strength. By eliminating self-citations, coauthor cross citations and normalizing, we find the strongest citation relationship is from Burrell Q. L. to Egghe L., the second strongest is from Yu G. to Egghe L. From the perspective of mutual cross-citation, the above two pairs of authors, Yu G., Bonitz M and Schubert A. or Burrell Q. and Glanzel W. have relatively intimate relationship. Zitt M. has the highest citing frequency and Braun T. has the highest cited frequency. Glanzel W. has many coauthors in the prolific author group and these authors happen to be his major cross-citation authors, so his rankings in many aspects have dropped. Both Schubert A. and Leydesdorff L.'s ranking in centrality measure have dropped, because they have large number of citing authors that have changed their centrality degree. But the essential core–edge structure of authors remains unchanged.

Similar processing is conducted to the highly productive-highly cited author matrix. Result shows that authors like Vinkler P., Schubert A., Leydesdorff L. and Glanzel W. have very high total number of citing authors, thus their central position as strong citing strength group has been replaced by authors like Bonitz M. and Burrell Q. L. Meanwhile strong cited strength of authors like Braun T., Narin F. and Schubert A. has become prominent. This reflects their prominent contribution and high impact in the scientometrics field. All in all, influence of collaborative relationship on author cross citations should not be neglected. It's also necessary to do standardization work according to total number of citing authors. These processes can help us to discover more clearly the real citation relationship among authors, which is of great help to build up author academic relationship mining model in the future. Due to limitation of time and capacity, only dominant collaboration is taken into consideration here. But practical research team and potential collaborative relationship are not analyzed. These problems will be solved in future studies.

(4) Drawing lessons from the routine of co-citation analysis, we can also classify authors by their cross-citation relationship in order to help summarize research patterns, find research communities, and discover research hot topics and boost the development of disciplines in the future studies. The study combined factor analysis and cluster analysis to divide core authors in scientometrics field into 8 clusters, namely Informetrics and Bibliometrics, Dynamics of Science and Technology, Citation and Science Communication, Scientometrics Indicators and Basic Research Assessment, Scientific Indicators and Evaluation of Research Performance, Application Research of Scientometrics, Bibliometrics Indicators and Mapping of Science, Patent-metrics and Linkage between Science and Technology. Since one author may involve several areas, the classification doesn't mean they're separated but rather the other way around. It should be noticed that the subject classification mentioned in the study is based on author cross-citation relationship of the communication level, which is quite different from the author classification based on author co-citation analysis. It demonstrates active areas' division of author communications rather than impact areas' division. The type of classification is quite different from previous conclusions based on co-citation analysis or author bibliographic-coupling analysis (Wang 2010). The difference lies in that the former one is more related to current prevailing study areas while the latter one reveals deeper and wider subject areas. Both

have their own emphasized side. Besides, Hou et al. (2008) did a classification to research subjects and groups of scientometrics based on cooperation network, which is similar but different from the above 3 types of citation analysis. In future studies, the authors will comparatively explore knowledge structure analysis upon cooperation network, co-citation analysis, coupling network and cross-citation network in order to completely and thoroughly reveal discipline structure and scholar communities of scientometrics field.

Currently, author cross-citation analysis is still a new study view. It shares similarity with citation identity and citation map in many ways and could be complementary. Many methodologies and tools of widely used in co-citation analysis can be introduced to explore the cross-citation relationship exploration. The study has been an explorative one. The authors sincerely hope the tiny piece of work could attract more attention from peer scholars. But there are some limitations in the research methods and data source selection of this study. It is based on the number of citations only, and the way and type of the mention of the references are not investigated, which follow next time. It is also a limitation to the study that it is restricted to Scientometrics journal, only. Scientometrics is the leading journal but there are also other journals dealing with scientometrics. The cross-citation analysis done here is an explorative work; more typical journals will be included to do deeper study in the future, such as JASIST, Journal of Informetrics, and so on.

In the future studies, the authors will further research on author cross-citation relationship aiming at discovering more valuable information and eventually make progress to the development of scientometrics field.

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Appendix

See Table 11.

Table 11 Standardized cross-citation matrix among core authors (part of it)

	Garfield E.	Glanzel W.	Braun T.	Egghe L.	Leydesdorff L.	Narin F.	Schubert A.	Moed H. F.	Small H.	Van Raan A. F. J.
Garfield E.	**0**	0	0.0047	0	0	0.0047	0	**0**	**0**	0
Glanzel W.	0.0165	**0**	**0**	0.018	0.0075	0.015	**0**	0	0.0075	0.009
Braun T.	0.0295	**0**	**0**	0	0.0054	0.0241	**0**	0.0107	0	0.0054
Egghe L.	0.0063	0.0314	0.011	**0**	0	0	0.0094	0.0047	0.0016	0.0078
Leydesdorff L.	0.013	0.0028	0.0186	0.0009	**0**	0.0186	0.0009	0.0084	0.0204	0.0065
Narin F.	0.0149	0	0	0	0	**0**	0	0	0.0299	0
Schubert A.	0.0165	**0**	**0**	0.0007	0.0033	0.0079	**0**	0.0039	0.0033	0.002
Moed H. F.	**0**	**0**	0.0417	0.0052	0	0.026	0.0469	**0**	0.0156	**0**
Small H.	**0**	0.003	0	0	0.003	0.0121	0	0	**0**	0.003
Van Raan A. F. J.	0.0038	0.0115	0.0115	0.0191	0.0076	0.0191	0	**0**	0.0229	**0**

Bold numbers indicate coauthor or self-citation relationship between each other

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