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An author co-citation analysis of 37 years of iMetrics

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Abstract

Purpose – This research aims to examine the intellectual structure of iMetrics through author co-citation analysis.

Design/methodology/approach – This research uses common techniques in bibliometrics and social network analysis. It analyses 5,944 records from the Web of Science in the field of iMetrics that are published between 1978 and 2014.

Findings – Findings indicated that researchers including "Garfield", "Egghe", "Glanzel", "Leydesdorff" and "Price" have received many co-citations. The author co-citation analysis in iMetrics resulted in eight thematic clusters, including "theoretical foundations and citation analysis", "sociology of science", "science mapping and visualization", "network analysis", "classic laws of bibliometrics", "webometrics", "technometrics" and "miscellaneous". "Theoretical foundations and citation analysis" is the biggest cluster which comprises 59 authors. The results suggest the crucial role of price medallists in shaping the intellectual structure of knowledge in iMetrics.

Originality/value – Extracting the patterns embedded in the knowledge structure of iMetrics studies provides beneficial information for both researchers and policymakers. This research study is valuable that used an appropriate set of records regarding both recall and precision. Furthermore, this study helps us better understand the characteristics of iMetrics, its subject areas, and the prominent authors in those areas.

Keywords Intellectual structure, Bibliometric analysis, Citation analysis, Author co-citation analysis, iMetrics

Paper type Research paper

1. Introduction

Nowadays, iMetrics techniques are used in many disciplines for better understanding of the data. According to Milojevic and Leydesdorff (2013):

> Terms such as bibliometrics, scientometrics, informetrics, and webometrics have been used to describe quantitative studies of bibliographies (books and libraries), science, information phenomena, and World Wide Web. Although these terms emerged in different contexts and stemmed from different disciplinary backgrounds, they fairly quickly started being used interchangeably. These terms can all be considered as manifestations of a single research area with similar objectives and methods, which we call "information metrics" or iMetrics.

"Metric studies have been developed as a subsidiary branch of library and information science over time" (Khasseh *et al.*, 2017). As noted by Milojevic and Leydesdorff (2013):

> [. . .] iMetrics is a very active research field experiencing a growth that justifies the talk about an explosion of iMetrics literature in the last decade. However, during the 1980s and 1990s, iMetrics was forming and searching for its identity somewhere between science and technology studies and information science, the research area became more established as it became closer to information science during the 1990s.

Nevertheless, as they argue, iMetrics has well detached itself from information science and achieved an independent socio-cognitive identity. Considering the emergence and gradual

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evolution of the field, it is necessary to illustrate a comprehensive and all-encompassing picture of research in this field and to investigate its knowledge and intellectual structure to explore the subject clusters and topics over a long-term period by applying a scientific method.

The study on the knowledge structure of technical and scientific fields is possible through various techniques and approaches, for example, the co-citation analysis which originated from citation analysis. This technique leads to the determination of the main concepts and subject categories in a given field. In addition, it uses the advantages of social network analysis and, consequently, represents the possible relation between individual authors, a group of authors, documents, journals, and so forth.

The study on the knowledge structure of a field consequently results in exploring and explaining the hidden relations among bibliographic entities (Van Eck and Waltman, 2010). Bibliographic analysis, alongside the use of the sociology of science, offers an appropriate perspective on definitions, borders and studies in a scientific field. The ontology and the epistemology of the social structure of knowledge make it possible to identify the concepts and paradigms dominated in the structure of a field (Hyung Kim, 2012) and represent a real image of that field. With such an idea, the current research investigates the intellectual structure of the knowledge within the iMetrics literature through author co-citation analysis. Both researchers and policymakers may benefit from the patterns that are extracted from the knowledge structure of iMetrics studies. The main questions of this research are:

RQ1. How is the frequency of citations distributed amongst the authors in the field of iMetrics?

RQ2. Based on hierarchical cluster analysis, how are the authors of the iMetrics field clustered?

RQ3. Which topics are the most attractive in the clusters of the iMetrics field?

RQ4. Which authors are the most influential in the clusters of the iMetrics field?

2. Literature review

The analysis of references via the co-citation studies makes it possible to represent the intellectual structure of different disciplines. Since its introduction in 1973 by Marshakova (1973) and Small (1973), the co-citation analysis has been widely used as a quantitative bibliometric method to study the structure of several research areas including: sociology (Lazer *et al.*, 2009), entrepreneurship (Schildt *et al.*, 2006), international management (Acedo and Casillas, 2005), sport management (Hyung Kim, 2012), higher education (Tight, 2008), e-learning (Chen and Lien, 2011), biology (Boyack and Klavans, 2010), operations management (Pilkington and Meredith, 2009), information behaviour (González-Teruel *et al.*, 2015), information management systems (Shiau *et al.*, 2015), architecture (Lee and Chung, 2014), knowledge management (Subramani *et al.*, 2003; Walter and Ribière, 2013), communication (Kim, 2012), hospitality management (Köseoglu *et al.*, 2015), teacher education (Özçınar, 2015) and anti-cancer research (Xie, 2015).

A review of the related literature shows that the iMetrics research using the author co-citation analysis has not been investigated, and the most relevant studies on the author co-citation analysis have been mainly conducted in library and information science (LIS). For instance, in one of the studies conducted by the author co-citation analysis, De-Moya-Anegon *et al.* (1998) identified the structure of LIS in Spain during the period from 1985 to 1994. They showed that "informetrics" and "libraries" are two major subjects in LIS research in Spain. Astrom (2002) used a combination of the author co-citation analysis and the co-word analysis to examine 1,135 Social Science Citation Index records from LIS journals during 1998-2000. Again, the findings showed that "bibliometrics" is one of the main subject areas. Chen *et al.* (2010) examined the structure and dynamics of co-citations in the field of information science as defined by 12 journals published between 1996 and 2008. Part of their results indicated that "bibliometric analysis", "webometric analysis" and "journal co-citation analysis" are among the largest author co-citation clusters. In one of the other studies, Egghe (2012), to examine the five-year performance of the *Journal of Informetrics*, overviewed articles that have been published between 2007 and 2012. This study revealed that more than 50 per cent of the papers deal with citation analysis and/or h-type indices. The common points reached in the abovementioned studies is that iMetrics is one of the main topics in LIS.

In most of the related studies discussed above, the major emphasis was on LIS, and iMetrics was not exactly seen as an independent area. However, despite the shared beliefs, iMetrics is currently known as a distinct research field having an independent socio-cognitive identity. For the same reason, the present study intended to consider it as a distinct field of research.

In total, the use of co-citation analyses has increased in recent years for depiction of the intellectual structure of scientific knowledge in various research fields. In addition, reviewing related literature showed that recently, iMetrics researchers have tended to orientate towards the procedures of network analysis and science visualization. This trend can be seen in different fields. In addition, researchers argue that author co-citation analysis is an effective method for achieving deep vision and a complete perspective on the intellectual structure of the field at hand (Jeong *et al.*, 2014) and it has emerged as a relatively stable research pattern for the exploration of scientific knowledge structure (Wang *et al.*, 2012).

3. Data and methods

This research applied co-citation analysis and social networking analysis. The research population comprised iMetrics papers indexed in the Web of Science (WoS) database during 1978-2014. It is noteworthy that in research on fields, such as bibliometrics, informetrics, webometrics and, in general, iMetrics, the lack of a justified and appropriate statistical population can be seen. Nevertheless, the selection of primary data is important in every iMetrics study as it directly affects results and findings. It is better to include comprehensive primary data. Considering this main point, the statistical population of this research included all papers published in *Scientometrics* and the *Journal of Informetrics*, as well as iMetrics papers published in the six journals including the *Journal of American Society for Information Science and Technology (JASIST)*, *Information Processing and Management*, *Journal of Documentation*, *Journal of Information Science*, *Research Evaluation* and *Research Policy*. The reason for selecting these journals was that they published the most papers in the field of iMetrics (Milojevic and Leydesdorff, 2013). Moreover, *Scientometrics* is the first specialized journal in the iMetrics field that has been published since 1978 and developed the field (Leydesdorff *et al.*, 2014; Milojevic and Leydesdorff, 2013). Therefore, the time span of 1978-2014 was selected for this research.

At first, all scientific productions in the WoS published in the above-mentioned eight journals were extracted. Then, articles and proceedings were selected. All papers published in *Scientometrics* and the *Journal of Informetrics* were included. Based on a two-tiered procedure mentioned in Milojevic and Leydesdorff (2013), the papers irrelevant to the iMetrics field in the six journals including *Journal of American Society for Information*

Science and Technology (JASIST), *Information Processing and Management*, *Journal of Documentation*, *Journal of Information Science*, *Research Evaluation*, and *Research Policy* were excluded. Milojevic and Leydesdorff (2013) tested a routine to distinguish between the two sets using two criteria:

(1) at least one reference to either *Scientometrics* or the *Journal of Informetrics*; and

(2) specific title words.

The first criterion (reference criterion) was that each paper published in the *Journal of American Society for Information Science and Technology (JASIST)*, *Information Processing and Management*, *Journal of Documentation*, *Journal of Information Science*, *Research Evaluation* and *Research Policy* which cited in one of the papers published in *Scientometrics* and the *Journal of Informetrics* was included. In other words, following Milojevic and Leydesdorff (2013), the citation to papers published in *Scientometrics* and the *Journal of Informetrics* as the main journals of iMetrics was the criterion for separating the papers published in the other six journals in the iMetrics field from those of the non-iMetrics field. The software ISI.exe was used for records' screening.

Many related papers were retrieved by applying this method. Nevertheless, it was probable that some related papers published in these journals had no citation to *Scientometrics* or the *Journal of Informetrics*. For retrieving such papers, the second criterion (keyword search) was used. Some commonly used and highly frequent keywords in the field extracted from previous research were used in the following search strategy that resulted in some other related items:

TITLE = ("informetric*" OR "bibliometric*" OR "scientometric*" OR "webometric*" OR "citation*" OR "cite" OR "*citation" OR "indicator*" OR "productivity" OR "mapping" OR "h-index" OR "h index" OR "Hirsch index" OR "*index" OR "co-autho*" OR "coautho*" OR "impact factor*" OR "link analys*" OR "link structure" OR "patent analys*" OR "Zipf*" OR "Bradford*" OR "Lotka*" OR "collaboration network*" OR "scientific collaborat*")

Finally, considering the attempt to achieve a complete statistical population, 5,944 papers in the iMetrics field were identified and analysed. As shown in Table I, the majority of these papers were published in *Scientometrics*, *JASIST* and *Informetrics*.

Journal name	No. of all document types	No. of articles and proceedings	No. of iMetrics articles (after applying reference and keyword criteria) Articles based on keyword search	Articles based on reference criterion	No. of iMetrics articles
Scientometrics	4,003	3,556	-		3,556
JASIST	5,194	3,503	758	87	845
Journal of Informetrics	510	463	-		463
Research Policy	2,680	2,248	327	26	353
Research Evaluation	429	384	213	18	231
Journal of Information Science	1,941	1,434	146	28	174
Information Processing and Management	2,965	1,968	145	43	188
Journal of Documentation	2,714	866	91	43	134
Total	20,436	14,422	-		5,944

Table I. Frequency of iMetrics papers published in the studied journals

After retrieving 5,944 records about the iMetrics field and data file integration based on the research objectives, the structure of knowledge in the iMetrics field was studied using the co-citation analysis. In this research, the co-citation techniques recommended by Ding *et al.* (1999), White (2003), White and Griffith (1981) and White and McCain (1998) were used. First, all reference lists of the 5,944 records were retrieved by BibExcel and the names of authors of each of these items were recorded and saved in an individual file. The files were amended and edited. Thereafter, it was required to decide on the threshold of the co-citation analysis. Bradford's one-third law was applied for determining the appropriate number for inclusions of influential authors in the co-citation. Of the total 169,752 co-citations, 170 top researchers had one-third of all co-citations (56,044 co-citations). For the co-citation analysis and developing square matrices and depicting the co-citation map, the information on these 170 top authors was used so as to determine the intellectual structure in iMetrics. After determining the threshold for including authors in the co-citation analysis, square matrices and correlation matrices were provided by using BibExcel and UCINET, respectively. The final steps in the co-citation analysis – that is, the hierarchical clustering – were carried out using SPSS. Related clusters were extracted using SPSS software and between-groups method, and then, publications of authors in each cluster were found and studied in terms of content and subject expertise. Next, authors' research interests were extracted and the main subject areas of clusters were detected.

4. Results

For answering *RQ1* which considers the frequency distribution of iMetrics authors based on their received citations and co-citations, analysing descriptive data based on citation counts (influence) revealed that Leydesdorff was the most highly cited author who received 4,780 citations in total. Glänzel (with 4,074 received citations) and Van Raan (with 3,244 received citations) were second and third, respectively. Table II shows the total number of citations received by the authors. These authors heavily influenced the research on iMetrics and its future development. In spite of their few research studies, some authors received many citations. This is a sign of their considerable influence on the field.

The connections among author co-citations represent the relations between two authors regarding subject proximity in their works. The more the connections between two authors,

Rank	Researcher	Citation	Article	Rank	Researcher	Citation	Article
1	Leydesdorff L	4,780	146	16	Ingwersen P	1,084	24
2	Glänzel W	4,074	134	17	Martin BR	1,055	15
3	Van Raan AFJ	3,244	76	18	Tijssen RJW	1,052	39
4	Moed HF	2,543	62	19	Meyer M	1,035	28
5	Schubert a	2,513	81	20	McCain KW	983	22
6	Thelwall M	2,173	113	21	Cronin B	947	33
7	Egghe L	2,059	134	22	Persson O	890	25
8	Rousseau R	2,027	136	23	Katz JS	832	8
9	Braun T	1,778	60	24	Etzkowitz H	818	2
10	Van Leeuwen TN	1,762	58	25	Bordons M	760	31
11	Narin F	1,446	20	26	Vinkler P	715	34
12	Bornmann L	1,429	83	27	Rafols I	710	18
13	Small H	1,325	29	28	Vaughan L	678	23
14	White HD	1,298	15	29	Boyack KW	674	19
15	Daniel HD	1,093	44	30	BarIlan J	670	31

Table II. Top 30 iMetrics researchers based on total citations received the more the subject proximity in their research works can be expected. Moreover, the more the node size in the co-citation network, the more influential the author is in the mapped network. Therefore, the author co-citation clusters provide useful information on similar research topics and the importance of their authors (Xie, 2015). For visualizing the intellectual structure in iMetrics, the author co-citation analysis was used. The results of the author co-citation analysis are explained as follows.

4.1 Co-citation maps of iMetrics research

Figure 1 depicts the density view of the author co-citation map of the 170 studied authors. Some authors, such as Garfield, Egghe, Glänzel, Leydosdorff and Price, received more connections as the co-citation rate and the network density around them was more than that of others (red parts). Figure 2 illustrates the frequency distribution of co-citations among the top 20 researchers. Based on the co-citation data and information in Figures 1 and 2, Garfield had the highest co-citation rate (2,515 co-citations) in iMetrics. However, there were only 12 papers by his name out of 5,944 papers studied here. On the other hand, Leydosdorff was in the second rank by authoring 146 papers and receiving 2,303 co-citations. Egghe and Glänzel were placed in the third and fourth ranks, respectively. Of interest in the findings was that some authors (such as Price, Small, White, Cronin, Hirsch and Merton) were co-authored frequently despite their few works on iMetrics. This reveals their major influence on the formation and development of the intellectual structure of this field. This is detailed in the section on analysing the subject clusters.

As shown in Table III, the couple of "Garfield–Moed" has the highest frequency among iMetrics authors. Among the 30 highly frequent co-citation couples, Garfield had the first rank and was one of the parties in 11 couplings. The second and third ranks belonged to the bibliographic couplings "Egghe–Rousseau" (with 238 co-citations) and "Egghe–Hirsch" (with 235 co-citations), respectively. Table III shows the co-citation frequency of the 30 top couples whose, accordingly, publications can be studied and common research interests can be identified.

For example, one research interest of the coupling "Egghe–Hirsch" is introducing and h-index-related indicators studied. The coupling "Small–White" is famous for their interest in research on the co-citation analysis. It is noteworthy that accurate exploration of common research interests and relations among authors needs creating square matrices and consequent application of multivariate analysis methods, including, among others, cluster analysis.

4.2 Hierarchical cluster analysis of iMetrics research

For answering *RQ2* which intended to identify the subject clusters in iMetrics studies, hierarchical clustering was used. The hierarchical clustering algorithms available in SPSS and UCINET build a cluster hierarchy that is commonly displayed as a tree diagram called a *dendrogram*. Based on a square matrix provided by using the information on the 170 highly cited authors, a hierarchical clustering was prepared in this step of the study (Figure 3). The dendrogram mapped in the study provided some useful information on the clusters, the authors included in each, and the intellectual structure of the field concerned. The horizontal axis of the dendrogram represents the distance or dissimilarity between clusters. The vertical axis represents the objects (in this case, names of authors) and clusters. The number in front of each author represents the code given by SPSS which is based on an alphabetical sorting of authors.

With regard to the most attractive topics uncovered by the hierarchical cluster analysis, as the dendrogram shows, the intellectual structure in iMetrics is formed from eight main

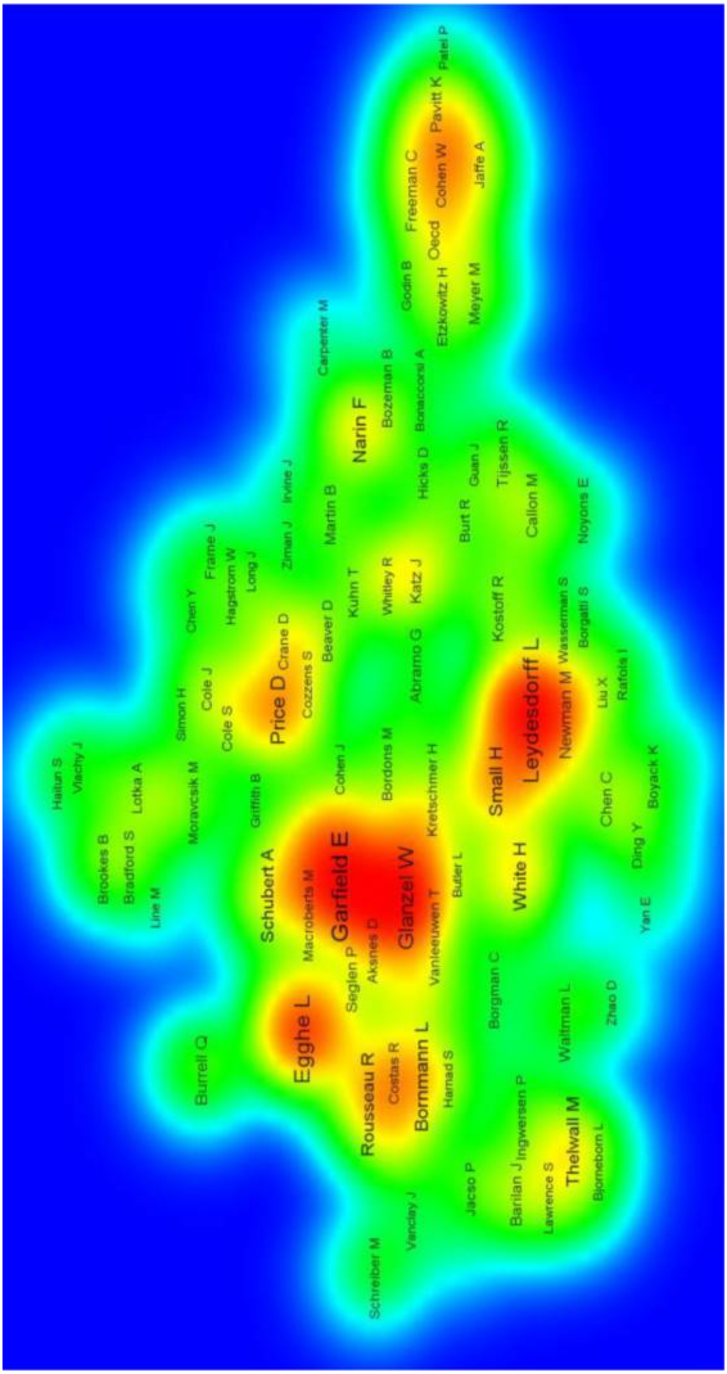


Figure 1.
iMetrics author co-citation map based on density view

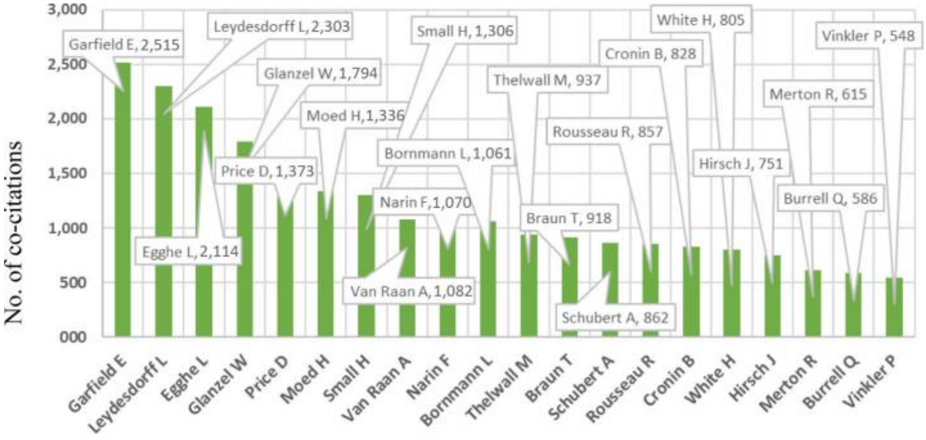


Figure 2.
Frequency distribution of co-citations among the 20 top researchers

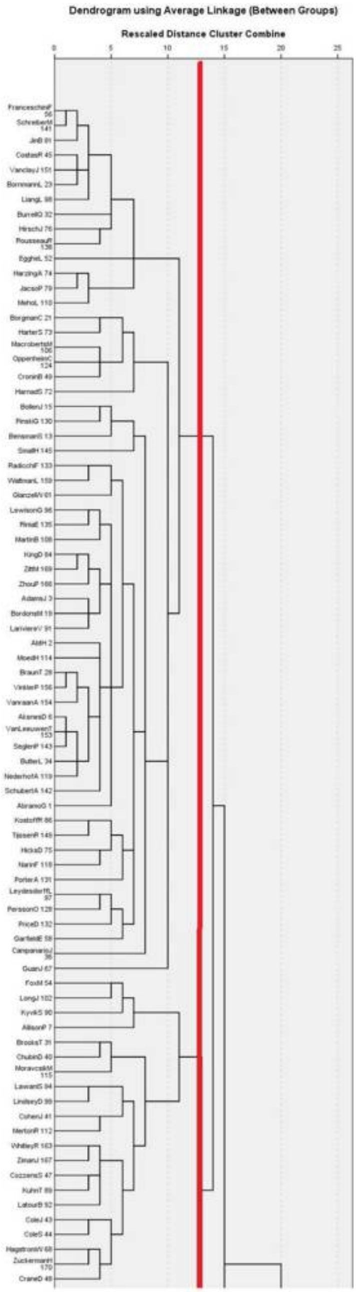
Table III.
Frequency distribution of the 30 co-citation couplings

Rank	Co-citation coupling	No. of co-citation	Rank	Co-citation coupling	No. of co-citation
1	Garfield–Moed	382	16	Leydesdorff–Small	242
2	Egghe–Rousseau	338	17	Leydesdorff–Moed	240
3	Egghe–Hirsch	335	18	Egghe–Garfield	240
4	Glänzel–Moed	322	19	Glänzel–Hirsch	237
5	Garfield–Small	313	20	Braun–Glänzel	219
6	Garfield–Glänzel	307	21	Egghe–Van Raan	217
7	Garfield–Leydesdorff	302	22	Cronin–Garfield	211
8	Moed–Van Raan	294	23	Garfield–Narin	210
9	Glanzel–Schubert	290	24	Glänzel –Rousseau	210
10	Garfield–Price	288	25	Garfield–Schubert	202
11	Glanzel–Van Raan	285	26	Braun–Garfield	202
12	Egghe–Glänzel	283	27	Small–White	199
13	Bornmann–Hirsch	249	28	Moed–Schubert	199
14	Glänzel–Leydesdorff	247	29	Braun–Schubert	195
15	Garfield–Van Raan	244	30	Burrell–Egghe	194

clusters; the greatest and smallest clusters include 59 and 8 authors, respectively. Table IV shows the information on the clusters and the authors included in each.

4.3 Attractive topics and influential authors in the clusters of iMetrics

For answering *RQ4* and *RQ5* that concerns the exploration of the influential authors in the development of each subject cluster, there was a need to accurately study the works and research interests of the authors included in the specific cluster and to compare them with those of other researchers in the cluster. It resulted in determining the main subject of the cluster. For this, the authors' names were searched through Publish or Perish, Google Scholar and, sometimes, their personal webpages. Then, their papers (including journal articles, conference proceedings and published books) were collected. Each author's papers were studied for exploring his/her study field(s) and research interest(s). When studying the researchers' works, the focus was on those items with highly frequent co-citations.



(*continued*)

Figure 3.
Dendrogram extracted from hierarchical clustering of author co-citations in iMetrics

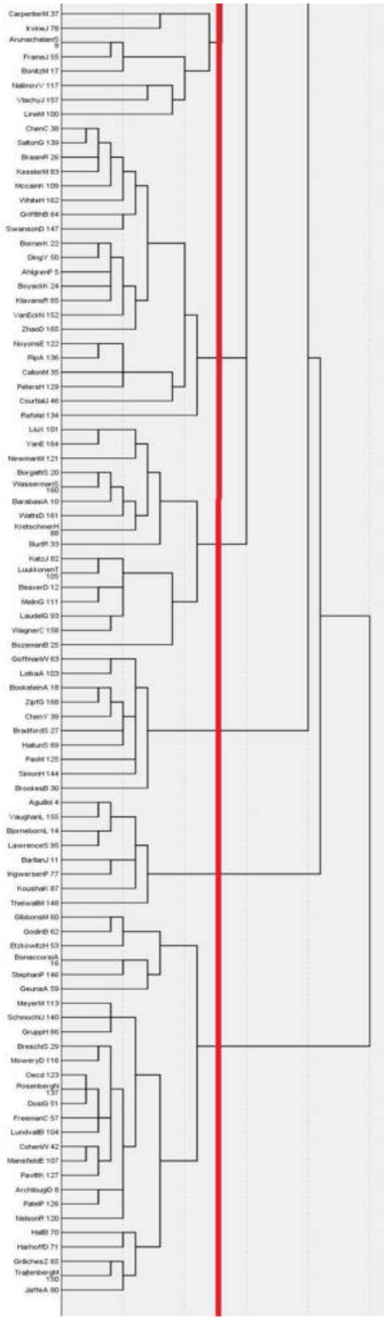

CarpenterM 37
IrvineJ 78
ArunachalamS 9
FrameJ 55
BonitzM 17
NalimovV 117
VlachyJ 157
LineM 100
ChenC 38
SaltonG 139
BraamR 26
KesslerM 83
MccainK 109
WhiteH 162
GriffithB 64
SwansonD 147
BornerK 22
DingY 50
AhlgrenP 5
BoyackK 24
KlavansR 85
VanEckN 152
ZhaoD 165
NoyonsE 122
RipA 136
CallonM 35
PetersH 129
CourtialJ 46
RafolsI 134
LiuX 101
YanE 164
NewmanM 121
BorgattiS 20
WassermanS 160
BarabasiA 10
WattsD 161
KretschmerH 88
BurtR 33
KatzJ 82
LuukkonenT 105
BeaverD 12
MelinG 111
LaudelG 93
WagnerC 158
BozemanB 25
GoffmanW 63
LotkaA 103
BooksteinA 18
ZipfG 168
ChenY 39
BradfordS 27
HallurS 69
PaoM 125
SimonH 144
BrookesB 30
AguilloI 4
VaughanL 155
BjornebornL 14
LawrenceS 95
BarIlanJ 11
IngwersenP 77
KousHaK 87
ThelwallM 148
GibbonsM 60
GodinB 62
EtzkowitzH 53
BonaccorsiA 16
StephanP 146
GeunaA 59
MeyerM 113
SchmochU 140
GruppH 66
BreschiS 29
MoweryD 116
Oecd 123
RosenbergN 137
DosiG 51
FreemanC 57
LundvallB 104
CohenW 42
MansfieldE 107
PavittK 127
ArchibugiD 8
PatelP 126
NelsonR 120
HallB 70
HarhoffD 71
GrilichesZ 65
TrajtenbergM 150
JaffeA 80

Figure 3.

Cluster no.	No. of researchers	Main subject of clusters	Researcher included in clusters
1	59	Theoretical foundations and citation analysis	Franceschini; Schreiber; Jin; Costas: Vanclay; Bornmann; Liang; Burrell; Hirsch; Rousseau; Egghe; Harzing; Jacso; Meho; Borgman; Harter; Macroberts; Oppenheim; Cronin; Harnad; Bollen; Pinski; Bensman; Small; Radicchi; Waltman; Glanzel; Lewison; Rinia; Martin; King; Zitt; Zhou; Adams; Bordons; Lariviere; Abt; Moed; Braun; Vinkler; Van Raan; Aksnes; Van Leeuwen; Seglen; Butler; Nederhof; Schubert; Abramo; Kostoff; Tijssen; Hicks; Narin; Porter; Leydesdorff; Persson; Prics; Garfield; Campanario; Guan
2	21	Sociology of science	Fox; Long; Kyvik; Allison; Brooks; Chubin; Moravcsik; Lawani; Lindsey; Cohen; Merton; Whitley; Ziman; Cozzens; Kuhn; Latour; Cole (J); Cole (S); Hagstrom; Zuckerman; Crane
3	8	Miscellaneous	Carpenter; Irvine; Arunachalam; Frame; Bonitz; Nalimov; Vlachy; Line
4	21	Science mapping and visualization	Chen; Salton; Braam; Kessler; Mc Cain; White; Griffith; Swanson; Borner; Ding; Ahlgren; Boyack; Klavans; Van Eck; Zhao; Noyons; Rip; Callon; Peters; Courtial; Rafols
5	16	Network analysis	Liu; Yan; Newman; Borgatti; Wasserman; Barabasi; Watts; Kretschmer; Burt; Katz; Luukkonen; Beaver; Melin; Laudel; Wagner; Bozeman
6	10	Classic laws of bibliometrics	Goffman; Lotka; Bookstein; Zipf; Chen; Bradford; Haitun; Pao; Simon; Brookes
7	8	Webometrics	Aguillo; Vaughan; Bjorneborn; Lawrence; Bar Ilan; Ingwersen; Kousha; Thelwall
8	27	Technometrics (innovation and patent)	Gibbons; Godin; Etzkowitz; Bonaccorsi; Stephan; Geuna; Meyer; Schmoch; Grupp; Breschi; Mowery; Oecd; Rosenberg; Dosi; Freeman; Lundvall; Cohen; Mansfield; Pavitt; Archibugi; Patel; Nelson; Hall; Harhoff; Griliches; Trajtenberg; Jaffe

Table IV. Detailed information on subject clusters formed in the Dendrogram

These clusters extracted from the hierarchal clusters are explained individually as follows:

4.3.1 Cluster 1. Considering the greatness of this cluster, including 59 authors, it appears that the cluster is the most influential in iMetrics studies. The bibliographic couplings "Moed–Garfield" (with 382 co-citations), "Egghe–Rousseau" (with 338 co-citations), and "Egghe–Hirsch" (with 335 co-citations) had the first, second and third ranks regarding co-citation frequency distribution, respectively. The inclusion of researchers in this cluster who had the most frequent co-citation rate among all authors in iMetrics represents the importance of the topics involved in this cluster in the intellectual structure of iMetrics. In other words, all 15 researchers with highly frequent co-citations belonged to this cluster. These authors included Garfield, Leydesdorff, Glänzel, Moed, Van Raan, Egghe, Price, Narin, Small, Cronin, Rousseau, Schubert, Braun, and Hirsch. Therefore, iMetrics studies have been heavily influenced by this cluster. As we know, the Derek De Solla Price Award is one of the acknowledging honours a scientist can achieve in iMetrics. Of 27 individuals that have won the award, 16 were included in this cluster, including Eugene Garfield (1984), Tibor Braun (1986), Henry Small (1987), Francis Narin (1988), András Schubert (1993), Anthony F.J. Van Raan (1995), Ben Martin (1997), Wolfgang Glänzel (1999), Ronald Rousseau (2001), Leo Egghe (2001), Loet Leydesdorff (2003), Péter Vinkler (2009), Michel Zitt (2009), Olle Persson (2011) and Blaise Cronin (2013).

Considering the study fields of the authors included in this cluster, the cluster was named "theoretical foundations and citation analysis". Some of these researchers introduced several methods and indicators in iMetrics that guide other researchers in conducting related research. For example, h- (introduced by Hirsch in 2005) and g-indexes (introduced by Egghe in 2006) are two scientometric indicators repeatedly used by researchers. Most research conducted by the researchers in Cluster 1 is related to these indicators. Several studies conducted by authors, such as Franceschini, Schreiber, Jin, Costas, Vanclay, Bornmann, Liang, Burrell, Hirsch, Egghe, Jacso, Waltman, Schubert, Van Leeuwen, Van Raan, Vinkler, Braun, Glänzel, Oppenheim, and Cronin, have discussed bibliometric indicators, especially these two indicators, especially h-index. These studies have been done and frequently cited immediately after introducing h- and g-indices.

Generally speaking, citation analysis is one of the main subjects discussed in Cluster 1. Garfield, Braun, McRoberts, Oppenheim, Cronin, Harnad, Bollen, Pinski, Bensman, Small, Radicchi, Zitt, Adams, Bordons, Lariviere, Abt, Aksnes, Butler, Kostoff, Persson, Tijssen, and Meho are of the highly-cited researchers in the field of citation analysis. Many researchers included in the cluster authored some papers on scientometric indicators (especially those related to impact factor), including among others, Bollen, Bensman, Zitt, Bordons, Lariviere, Van Leeuwen, Seglen, and Garfield.

The inclusion of researchers conducting many highly-cited and highly-co-cited research on iMetrics is one of the features of this cluster. Considering some of these researchers' stable placement in/and main influence on iMetrics, their research interests cannot be embedded in one specific iMetrics subfield. For example, some research by Leydesdorff in recent decades was in the fields of citation analysis, journal citation indicators, and co-occurrence indicators, as well as science mapping, national research evaluation, journal interdisciplinarity, and the innovation triple helix of university-industry-government relations. Schubert, Moed, and Vinkler are some other examples. Studies by Schubert on citation analysis, research performance evaluation, and international collaboration have been highly co-cited. As a highly-cited author, Moed carried out research on citation analysis, journal citation indicators, and academic research evaluation. As a one-authored researcher in most of his works, Vinkler focused on citation analysis, evaluation of scientific publications, h-index, and journal citation indicators. Glänzel studied several fields, such as citation analysis, h-index, journal citation indicators, and co-authorship. Narin considered citation analysis and science-technology relations in his studies.

Attempting to conduct some research and propose some instruments, Harzing expanded the commonly-used iMetrics indicators, such as journal and paper citation analysis indicators and h-index into the web. Van Leeuwen considered citation analysis and h-index as well as national research performance. Van Raan had some research on h-index and university rankings. Some researchers in the cluster, such as Price, dealt with the theoretical foundation of iMetrics, including the history of science and the sociology of science. Borgman's studies on scientific communications and Porter's interdisciplinarity and scientific knowledge have been highly cited. Martin, Nederhoff, Guan, and Tijssen focused on research performance evaluation by applying compound scientific indicators.

4.3.2 Cluster 2. This cluster comprises 21 researchers. Considering these researchers' interests and their highly-co-cited works, the cluster has been entitled "the sociology of science". Mary Fox published mostly on researchers' gender and juvenility, especially among female researchers. Scott Long focused on gender differences in scientific production and Svein Kyvik did so on age and gender differences in science production and productivity. As a sociology specialist, Allison considered inequalities in science and scientific production. Brooks' pioneering works published in the *JASIST* in the 1980s considered citation motivations, resulting in his winning of the Price Award in 1989. Chubin studied the field of science policy-making. Moravcsik investigated the fields of citation performance, quality, and patterns during the 1970s and 1980s, resulting in his winning of the Price Award in 1985. Lindsey's studies were in the field of the sociology of science regarding impact and productivity indicators in the sociology of science and scientific publication system in social sciences. As one of the main founders of the sociology of scientific knowledge, famous American sociologist, Merton published the book *The Sociology of Science*: *Theoretical and Empirical Investigations* and introduced the Matthew effect. He won the Price Award in 1995. Whitley studied the social and intellectual structures of science. Ziman investigated the social dimensions of science. Thomas Kuhn published a famous and highly-cited book on the history of science, entitled *The Structure of Scientific Revolutions*, and it has been translated into different languages worldwide.

This cluster also includes other famous researchers. The French author, Bruno Latour, published two highly-cited books in iMetrics (entitled *Laboratory Life: the Construction of Scientific Facts*, and *Science in Action: How to Follow Scientists and Engineers through Society*). Jonathan Cole had some research on social states of science and gender and social differences in scientific production. S. Cole had some research on age and research performance, the rewarding system in science, and the hierarchy of science. Hagstrom is one of the theorists in the sociology of science. Harriet Zuckerman is one of the specialists in the sociology of science. Crane defined the "invisible college".

Among the interesting findings about the researchers included in this cluster was that despite their high-citedness and co-citedness and their influence on the formation of the intellectual structure of iMetrics, most of them had no papers among the 5,944 papers studied. Another point that is worthy of attention is that the most influential works by the researchers in this cluster has been published as books and ones in non-book format have been published in the sociology journals, such as the *Social Studies of Science*, the *American Sociological Review*, and the *American Journal of Sociology*.

4.3.3 Cluster 3. Consisting of eight researchers, this cluster includes various subjects so that it cannot be restricted and defined. For instance, Maurice Bernard Line conducted some research on the half-life and obsolescence of scientific papers in the 1970s. Vlachy conducted various studies in iMetrics, especially by using citation analysis in common samples of scientific production in physics for identifying the innovative papers in this field. He won the Price Award in 1989. Another researcher was Vasily V. Nalimov from the Soviet Union, the winner of the Price Award in 1987. Bonitz is famous for further developing the Matthew effect. Frame conducted some research on scientific activities of several countries and international scientific collaboration in the late 1970s. Arunachalam focused on international scientific collaboration and scientific productions. John Irvine wrote some papers on scientific performance and won the Price Award in 1997. Carpenter conducted some studies on journal clustering and patent citation analysis in the 1970s and 1980s.

As noted above, it is not possible to include the various subjects in this cluster under a broad umbrella. Some subjects, such as national-wide and international-wide scientific collaboration, iMetrics in general, mathematics in science, worldwide scientific distribution, citation patterns, and science evaluation can be seen in this "miscellaneous" cluster.

4.3.4 Cluster 4. This cluster consists of 21 researchers. It appears that the subject of the cluster is "mapping and visualizing science". Chaomei Chen, the designer of SiteSpace software, performed many research studies in science visualization patterns. Braam produced various works on mapping science, co-citation techniques and intellectual structure analysis in the late 1980s and early 1990s. Kessler conducted some studies on bibliographic coupling in the 1960s. As highly cited authors included in this cluster, Griffith, White and McCain helped iMetrics be developed and won the Price Award in 1997, 2005 and 2007, respectively. Borner had influential studies on visualization of science, and Ding had some studies on co-citation and co-word networks and the formation of the intellectual structure of scientific knowledge. Noyons studied the field of mapping science.

Boyack with influential works on the map of science in the first decade of the twenty-first century and those on co-citations and bibliographic couplings, Klavans with important works on the map of science published in the *JASIST* and Jan Van Eck with VOSviewer software for mapping and visualizing science introduced in 2010 are researchers included in this cluster. Zhao's main research tended towards author co-citation analysis and author bibliographic coupling analysis. Courtial and Peters have been influential authors in co-word analysis, network analysis and citation analysis. Rip and Callon had a role in developing the cluster with their focus on science maps and co-word maps in their original research.

4.3.5 Cluster 5. Based on the names and research interests of 21 authors having a role in formation and development of this cluster, it is named "social network analysis". Yan, Liu and Newman studied network analysis, co-authorship and centrality in co-authorship networks. The studies by Newman in the early years of the twenty-first century on network analysis and co-authorship networks have a significant role in the development of the cluster. Borgatti had a role in this cluster by introducing some instruments in network analysis and information visualization, especially UCINET and NetDraw in 2002. However, he did not publish these highly cited papers in iMetrics journals. Wasserman introduced some methods and applications for social network analysis in his book published in 1994 by Katherine Faust's contribution. Barabasi also studied social networks. Watts conducted many research studies on networks and science maps, and one of his papers published in *Nature* in 1998 in iMetrics was highly cited. Kretschmer published many papers on co-authorship network. Burt's studies on structural gaps and social capital were highly cited. Katz's research on scientific collaborations in the 1980s had a part in developing the cluster. Other authors, including Luukkonen, Beaver, Melin, Laudel, Wagner and Bozeman, studied co-authorship networks and scientific collaborations.

4.3.6 Cluster 6. It appears that this cluster can be named "bibliometric classic laws" that includes ten researchers, three of them famous for paving the way to subsequent studies on the field: George Zipf with his "law of the least effort", Samuel Bradford with his law of scattering and Alfred J. Lotka with his law of frequency distribution of scientific productivity. Consequently, most authors included in this cluster studied these bibliometric laws. Pao with Pao's law (1985) which is based on Lotka's law, Brookes with studies on Bradford's law and Bradford-Zipf's scattering and Chen with studies on these laws and their possible relations are included in this cluster. Simon published a highly cited paper on normal distribution functions in 1955. Haitun, Bookstein and Goffman studied Lotka's law and its application in acquisition, scientific productivity patterns and informetric distributions.

4.3.7 Cluster 7. Entitled "webometrics", this cluster consists of eight researchers. As a pioneer researcher in formation and development of the field, Mike Thelwall, the winner of the Price Award in 2015, conducted several research studies on webometrics, altmetrics, social media and sentiment analyses. Vaughan had some research studies on Web-based citation indicators and using the Web in iMetrics. Ingwersen, the winner of the Price Award in 2005, studied webometrics, Web impact factor and Web information retrieval. Bjorneborn, mostly with Ingwersen's contribution, conducted some studies on link and co-link analyses.

Other researchers in this cluster are Kusha with studies on Web citation analysis (especially in Google Scholar) and their use in evaluating scientific influence; Aguillo with some research on university rankings by webometric methods, the influence of universities on the Web and the use of Google Scholar for bibliometric studies; Lawrence with studies on Web search capacities, information accessibility on the Web; and Bar-Ilan with research about the use of iMetrics indicators in the Web environment, Web-based data collection for iMetrics studies, analysis of Web links and researchers' visualization in the social Web.

4.3.8 Cluster 8. Researchers with research interests, such as innovation, patents, invention, knowledge economy and economic analysis of innovations embedded in patents, are included, so this cluster's name can be considered as "technometrics (innovation and patent analysis)". Interestingly, most of these researchers published their papers in economics journals. National innovation systems and their importance were studied in some papers. Therefore, this cluster is closely related to economics as some specialists in economics, such as Bronwyn Hall, Dietmar Harhoff, Manuel Trajtenberg and Adam Jaffe, helped the formation and development of this cluster by conducting effective research and publishing highly cited papers on patent citation analysis. As a pioneer economist, Richard Nelson focused on research on innovation and national innovative organizations. Paula Stephan, as a Researcher in the Economics of Science at Georgia State University, and Aldo Geun, a Professor in the Department of Economics in the University of Toronto, published some papers on the economics of science and the economics of innovation. The main studies by Parimal Patel and Keith Pavitt are on innovation and policymaking in science. Mansfield focused on industrial innovation and patents and academic research impact on industrial development.

Cohen is one of the scientists included in this cluster who introduced the concept of "absorptive capacity" of knowledge in the area of research and development and innovation in 1990. Lundvall as an economist was included in the cluster due to studies on knowledge management and innovation performance. Dosi, Grupp and Breschi considered issues on innovation, co-invention and economics. Some authors, including Henry Etzkowitz, Andera Bonaccorsi and Martin Meyer, focused on the importance and placement of research in universities, industry–university relations and its effect on entrepreneurship, patents in university and industry, knowledge flow from science to technology and the triple helix of university–industry–government. These research studies have developed the mutual relationship between university and industry in developed countries. Consequently, academic research and industrial innovation act as the rings of the same chain. In addition to journals in the economy, some researchers included in this cluster published their studies in *Research Policy*.

5. Discussion and conclusions

The assumption for the co-citation analysis is that if two documents are frequently co-cited by other documents, they presumably take similar concepts and topics into consideration. By analysing documents that are frequently co-cited by other documents, it is possible to determine the patterns and the relations amongst the concepts of a field (Benckendorff, 2009), but these documents do not absolutely bear the same idea or concept. They may have related subjects, methodologies and so on. "Author co-citation analysis (ACA) has long been used as an effective method for identifying the intellectual structure of a research domain" (Jeong *et al.*, 2014). In this study, the intellectual structure of iMetrics was examined using author co-citation analysis.

The citation analysis of iMetrics revealed that 5,944 papers cited 175,561 sources. Although papers published in other journals, such as *JASIST*, *Research Policy* and *Journal of Informetrics*, have published some related highly cited papers in this field, papers published in *Scientometrics* were cited more than those published in other journals. This finding is reasonable, as this journal is as a major and an old source in the field of iMetrics. This is why most researchers in this field are interested in analysing papers published in *Scientometrics* (Chen *et al.*, 2012; Ding *et al.*, 2013; Dutt *et al.*, 2003; Egghe *et al.*, 2007; Erfanmanesh *et al.*, 2012; Hou *et al.*, 2008). Despite the fact that the *Journal of Informetrics* was published later, it belongs to the highly cited ones. This finding is in line with that of Egghe (2012).

The results of the research also revealed that Leydesdorff, Glänzel, Van Raan and Moed are amongst the highly cited authors in the iMetrics field. These ranks are expectable for Leydesdorff and Glänzel because they have received the first and the third ranks for the number of papers that they have published in the field, respectively. On the other hand, Van Raan and Moed have received considerable citations, but they have published relatively fewer papers. Some other researchers belong to the highly cited group but have a few contributions in publishing papers, including Narin, Small, White, Ingwersen, Martin, Meyer, McCain, Katz, Etzkowitz, Rafols, Vaughan and Boyack. Taking a closer look at their works shows why they are amongst the highly cited authors. For example, a paper by Etzkowitz and Leydesdorff entitled "The dynamics of innovation: from national systems and 'Mode 2' to a triple helix of university–industry–government relations", which was published in 2000 in *Research Policy* received increasingly numbers of citations. The papers published by Katz on scientific collaboration were also highly cited. One is a paper co-authored by Martin entitled "What is research collaboration?" that was published in *Research Policy* in 1997 and cited highly frequently. This result is in accordance with that of Abrizah *et al.* (2014) in which Glänzel, Van Raan and Schubert, respectively, were introduced as highly cited authors in iMetrics.

The co-citation analysis of authors revealed that Garfield was the most influential and highly frequent co-cited author in the field. The other highly co-cited authors are Leydesdorff, Egghe, Glänzel, Price, Small, White, Cronin, Hirsch and Merton. These researchers have had an essential role in developing concepts in iMetrics. For instance, Hirsch has introduced the h-index, as a qualitative scientific production indicator that integrates publication counts (productivity) and citation counts (efficacy) into one formula for achieving a more balanced indicator for scientists' scientific influences and Egghe introduced g-index for removing some weaknesses of the h-index.

Hierarchical clustering resulted in eight clusters: theoretical foundations and citation analysis, the sociology of science, mapping and visualizing science, network analysis, bibliometric classical laws, webometrics, technometrics and miscellaneous. The greatest and smallest clusters were "theoretical foundations and citation analysis" with 59 researchers and the "webometrics" cluster with 8 researchers, respectively.

Consequently, all 27 scientists who won the Price Award have had a substantial role in the formation, development and expansion of the iMetrics intellectual structure. These authors include 16 scientists in Cluster 1: theoretical foundations and citation analysis (including Garfield, Braun, Small, Narin, Schubert, Van Raan, Martin, Glänzel, Moed, Rousseau, Egghe, Leydesdorff, Vinkler, Zitt, Persson and Cronin), 3 scientists in Cluster 2: the sociology of science (including Brooks, Moravcsik and Merton), 3 scientists in Cluster 3: miscellaneous (including Vlachy, Nalimov and Irvine), 3 scientists in Cluster 4: mapping and visualizing science (including Griffith, White and McCain) and 2 scientists in Cluster 7: webometrics (including Ingwersen and Thelwall). Nevertheless, the scientists included in Cluster 1 (theoretical foundations and citation analysis) were cited and co-cited highly frequently and were more influential than other researchers included in the other clusters mentioned.

It can be concluded that the Cluster 1 ("theoretical foundations and citation analysis") is the main and the most common subject in iMetrics that is of interest for highly cited researchers. This finding is in line with that of Egghe (2012) who studied the papers published in a five-year time span in the *Journal of Informetrics* and concluded that a greater part of research studies in this field has focused on citation analysis and h-indices.

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