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Evolution of the Scientific Literature on Input–Output Analysis: A Bibliometric Analysis of 1990–2017

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Abstract: This study attempts to characterize the literature related to input–output analysis between 1990–2017 through bibliometric analysis technology based on the Science Citation Index and Social Sciences Citation Index databases. By means of bibliometric tools, this paper provides deep insights on the patterns of these articles, the most influential works and authors, and the emerging research topics. The results imply that China and the United States (USA) are the leading countries in terms of publication output. The Chinese Academy of Sciences is the most productive research institution, followed by Beijing Normal University and the University of Sydney. The Journal of Cleaner Production, Ecological Economics, and Energy Policy are the top mainstream journals in the input–output analysis-related field. Based on network analysis, this paper also discovers the hidden collaboration patterns and interrelations of countries, institutions, and authors. The bibliographic coupling and keywords concurrence networks are adopted to illustrate the input–output analysis evolution over time, and identify the current key research hotspots. The obtained results will help scientific researchers better understand the research status and frontier trends in this field, permit researchers to know the current research interests in the input–output analysis field, and provide useful information for further investigation and publication strategies.

Keywords: bibliometric analysis; input–output analysis; bibliographic coupling; co-occurrence network; network analysis

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1. Introduction

The original idea of input–output (IO) theory, which models all of the sectors of the economy via an input–output table, was firstly proposed by Wassily Leontief in the 20th century [1,2]. This great innovation in the economic field earned Leontief a Nobel Prize in 1973 [3]. Since then, the theory and methodology of input–output analysis has been developed rapidly. For example, the traditional static input–output model has been further developed into a dynamic integrated input–output simulation model [4]. The combination of the input–output model and system optimization technology is also an important development trend. Integrating the input–output model with linear programming, nonlinear programming, and dynamic programming models, an input–output optimization model can be established [5,6]. Input–output analysis not only has great development in terms of theory, methods, and tabulation, it has also been expanding in its application scope. Many researchers have extensively employed input–output models to environmental impact evaluations [7], energy analysis [8], and material metabolism measurements [9].

In general, researchers from a number of countries have carried out input–output-related research from various aspects, and these studies have been published in diverse journals. Therefore, an objective and quantitative evaluation on the rapid growing literatures in the field of IO analysis is desired. Bibliometric analysis can systematically assess the relative importance of scientific research results in a certain area, and characterize the geographical distribution of the field. After considering that the related research about those topics rose in the 1990s in our pre-information collection, the total majority of the published literature emerged in mainly 1990 to 2017. This study reveals the characteristics and evolution process of the global input–output analysis literature between 1990–2017. By using bibliometric analysis in combination with social network theory, in particular co-occurrence analysis and bibliographic coupling analysis, this paper helps to discover the hidden collaboration relationship among researchers from different institutions and countries, and the scientific fundamentals of this research field. With the assistance of various statistic indicators and science mapping, this paper will address the following questions:

- Who are the important contributing countries/institutions/authors in the IO analysis field?
- What are the collaboration relationships in the IO analysis field?
- What are the most influential papers in the IO analysis-related research?
- What is the evolution process of the research frontiers in the IO analysis field?
- What clusters of research focuses and topics can be found?

This sketch of the scientific structures would provide new insight into the breadth and depth of this body of knowledge. The obtained results will help scientific researchers better understand the research status and frontier trends in this field, permit researchers to know the current research interests in the input–output analysis field, and provide useful information for further investigation and publication strategy.

2. Data and Methods

2.1. Methodology

Bibliometric analysis is one of the most important tools for exploring library and information science. It has become an indispensable technology for evaluating the research status and trends of a given topic or a certain journal [10]. Based on statistical and mathematical methods, the bibliometric method can not only investigate the distributed characteristics, mathematical regularities, and patterns of the underlying science and technology, it can also reveal the research hotspots and future trends [11]. Through this, it will provide future research directions and guidelines for researchers or readers in this field. There are several bibliometric analysis methods. For example, word frequency analysis is a common method to calculate statistics on the content distribution and provide information for future trends. Citation analysis is widely applied to evaluate the quality of publications and the performance of countries/institutions/authors in the related field. Keyword co-occurrence analysis can determine the hotspots and knowledge structure in a certain discipline or research topic. If two keywords appear in one document at the same time, it may indicate that there must be some inherent connection between them. The higher the frequency at which those two keywords appear together, the closer their relationship. Co-occurrence analysis, when applied to the text in the bylines of articles, can be also used to discover the cooperation relationship among different authors or institutions.

With the emergence of bibliometric research, the visualization of a bibliometric network, which is also called science mapping, and helps display and excavate interrelationships between knowledge, has received more attention. Similar to other networks, the bibliometric networks consist of nodes and edges, where nodes can be authors, keywords, articles, and journals, while edges represent the relationships among the nodes [12]. According to graph theory, bibliometric network analysis can be used to map the interrelationships between various nodes, identify the communities/modules, detective the structural characteristics of complex networks, and reveal research hotpots [13]. Several different software packages have been developed for bibliometric analysis and visualization, e.g., Pajek [14], CiteSpace [15], Gephi [16], and VOS Viewer [17]. In this study, VOS Viewer was adopted to visualize and explore the networks.

2.2. Data Sources

The Institute for Scientific Information (ISI) Web of Science (WoS) has been extensively used as the data source in bibliometric analysis. In particular, its subfield databases, the Science Citation Index (SCI) and Social Sciences Citation Index (SSCI), include the most influential scientific literatures of different research fields. Therefore, in this study, the SCI and SSCI databases are selected as the data sources for searching for publications related to input–output analysis. The tag TS (=topic), which results in a search within the title, keywords, and abstract fields, was used for querying. The TS = ("input–output analysis" or "input–output model" or "input–output table" or "input–output technique*" or "input–output method" or "IO model" or "IO analysis" or "IO table" or "IO technique*" or "input–output framework" or "IO framework") was retrieved on 19 January 2018. As a result, there are total 3172 articles in English. While according to this query, not all of the articles with "input–output" words indicate the input–output theory proposed by Leontief. For example, some representations of the input–output model are for energy systems, some are for the input–output structure in neural network systems, some are for input–output in control systems. These irrelevant papers in other research fields should be excluded. In addition, in order to guarantee more accurate results, we further narrowed the investigation. In our work, article with "input–output" or "IO" appearing two or more times in the title/author keywords/abstract was considered as relative research in this field; otherwise, the record would be removed due to insignificant relation. After filtering the irrelevant and less relative publications manually, 2565 records were downloaded with author(s), titles, sources (journal title), languages, document types, author keywords, addresses, cited reference count, times cited, publisher information, page count, ISSN, and subject category information for further analysis in this study.

3. Results and Discussion

3.1. General Publication

Table 1 shows the characteristics of the input–output analysis-related publications from 1990 to 2017, including the total publication, total authors, total citations, average authors per publication, and average citations per publication for a certain year. In general, the steady growth trend of total publications indicates that there is an increase in the studies on the topic. The whole period can be divided into two stages: the first stage covers from 1990 to 2003, where the number of publications fluctuated but was still stable, and the second stage covers from 2004 to 2017, where the quantity of the relative literature increased rapidly (Figure 1). The fast increasing trend indicates that more and more researchers will use input–output analysis. In addition, currently the articles published between 1996–2012 gained relatively high average citations.

Table 1. Characteristics of publication by year (1990–2017).

Year	TP	AU	TC	AU/TP	TC/TP	Year	TP	AU	TC	AU/TP	TC/TP
1990	9	15	43	1.67	4.78	2004	46	107	1539	2.33	33.46
1991	16	30	118	1.88	7.38	2005	57	133	2364	2.33	41.47
1992	25	47	333	1.88	13.32	2006	58	144	1967	2.48	33.91
1993	24	54	257	2.25	10.71	2007	92	214	2798	2.33	30.41
1994	29	52	326	1.79	11.24	2008	102	241	2487	2.36	24.38
1995	24	52	404	2.17	16.83	2009	124	283	3431	2.28	27.67
1996	24	47	571	1.96	23.79	2010	128	317	3444	2.48	26.91
1997	27	55	719	2.04	26.63	2011	157	394	3505	2.51	22.33
1998	26	55	921	2.12	35.42	2012	146	454	3434	3.11	23.52

Table 1. *Cont.*

Year	TP	AU	TC	AU/TP	TC/TP	Year	TP	AU	TC	AU/TP	TC/TP
1999	34	71	797	2.09	23.44	2013	197	519	3807	2.66	19.33
2000	27	54	772	2.00	28.59	2014	216	612	2918	2.83	13.51
2001	32	69	833	2.16	26.03	2015	254	717	2437	2.82	9.59
2002	33	75	1318	2.27	39.94	2016	287	801	1185	2.79	4.13
2003	28	61	668	2.18	23.86	2017	343	986	448	2.88	1.31

TP: total publications; AU: the number of authors; TC: total citations; AU/TP: average authors per publication; TC/TP: average citations per publication. The results are based on information retrieved on 19 January 2018.

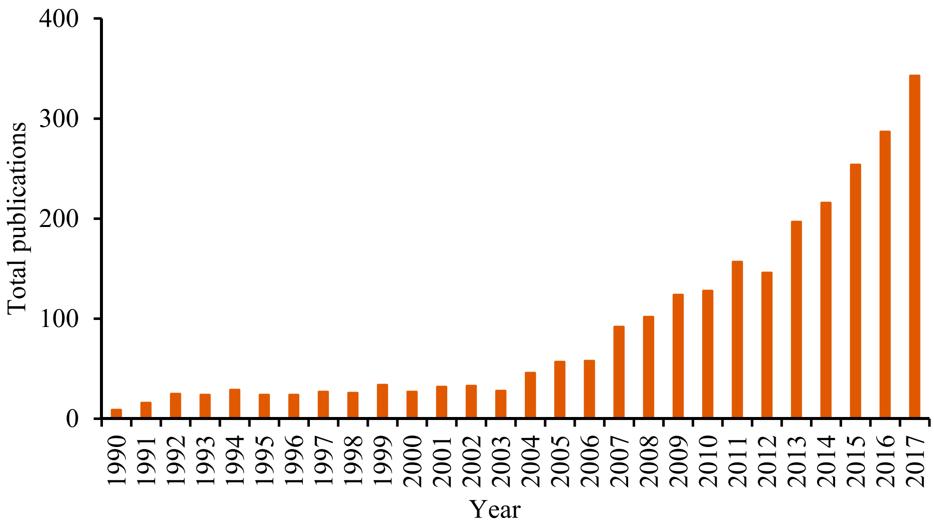

Figure 1. Publication output performance of input–output (IO) analysis during 1990–2017.

3.2. Distribution of Journals

There are a total of 584 journals published the related articles in the input–output analysis research field from 1990 to 2017. Table 2 shows the top 15 journals in this field. It can be found that these top 15 journals have contributed to about 44% of the total publications over the past 18 years, which indicates they are the mainstream journals in this field. Among them, the Journal of Cleaner Production is the most influential journal, with 151 publications in this field. It is followed by Ecological Economics (147 articles) and Energy Policy (137 articles). Applied Energy ranks sixth in term of total publication, but has the highest impact factor (7.182) among them. Ecological Economics and Energy Policy have the highest h-index (40) among the top 15 most productive journals. In general, *Applied Energy*, *Ecological Economics*, and *Energy Policy* are the key journals with a substantial influence on the input–output analysis research, and other key journals are also important to support such studies. In addition, Table 2 also provides the variation in these journals during different time periods. It can be found that the total publications in these journals are increasing. Some published journals have begun to pay more attention in this field, especially the *Journal of Cleaner Production*, whose relative publications are 0, 10, and 141 during the periods of 1990–1999, 2000–2009, and 2010–2017, respectively. By contrast, the rank of *The International Journal of Production Economics* has come down in recent years; as it was first for 1990–1999, 11th for 2000–2009, and 17th for 2010–2017.

3.3. Contribution of Countries/Institutions/Authors

In total, 4814 authors from 79 countries/areas and 1698 institutions made their contributions to the development of input–output analysis-related studies during the past 18 years.

Table 2. Top 15 key journals.

Journal Name	TP (%)	IF	H-Index	1990–1999		2000–2009		2010–2017	
				TP	R	TP	R	TP	R
Journal of Cleaner Production	151 (5.89)	5.715	22	0	-	10	10	141	1
Ecological Economics	147 (5.73)	2.965	40	7	6	63	1	77	5
Energy Policy	137 (5.34)	4.140	40	5	11	36	2	96	3
Economic Systems Research	129 (5.03)	2.691	24	0	-	22	4	107	2
Journal of Industrial Ecology	107 (4.17)	4.123	24	0	-	28	3	79	4
Applied Energy	75 (2.92)	7.182	20	1	36	8	14	66	6
Environmental Science & Technology	68 (2.65)	6.198	25	2	19	12	9	54	7
Energy	57 (2.22)	4.520	19	2	19	8	14	47	9
Energy Economics	51 (1.99)	3.199	19	10	4	6	18	35	10
Sustainability	48 (1.87)	1.789	10	0	-	0	-	48	8
International Journal of Production Economics	38 (1.48)	3.493	16	15	1	9	11	14	17
The International Journal of Life Cycle Assessment	33 (1.29)	3.173	17	0	-	17	5	16	15
Ecological Modelling	31 (1.21)	2.363	12	2	19	9	11	20	13
The Annals of Regional Science	28 (1.09)	0.694	8	6	9	13	6	9	24
Ecological Indicators	28 (1.09)	3.898	10	0	-	0	-	28	11

TP: the total publication in certain journal; %: the percentage in this field; IF: impact factor of the journal.

3.3.1. Contribution of Countries

According to the location of the author's affiliated institution, Table 3 lists the top 10 most productive countries' statistical information with regard to the number of total publications, the performance of international collaboration, and h-index. Among the 79 countries, China (630 papers) and the United States (USA) (623 papers) are clearly leading in terms of publications output, which are much more than the United Kingdom (UK) (230), Japan (192), and Spain (174). All of the countries show a favorable international cooperation relationship with other countries, especially Norway and Germany. Table 3 also shows their h-indexes. USA has the highest h-index (57), followed by China (47). A higher h-index indicates a relatively greater influence in this field. Figure 2 illustrates the annual publications of these top 10 most productive countries. The publications of these countries show an upward growth trend. The USA took a leading position in the early period from 1990 to 2010. However, China has enjoyed a rapid growth since 2009, and even surpassed the USA to rank first since 2014.

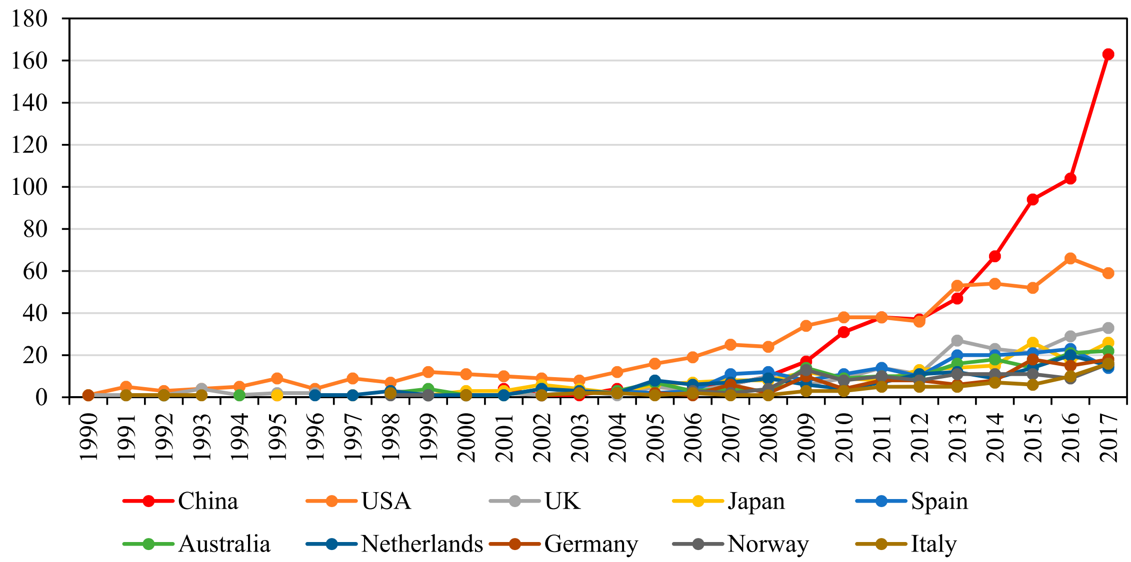

Figure 2. Annual publications of the top 10 most productive countries/territories.

Table 3. Top 10 most productive countries/territories.

Countries	TP	TP%	SP%	CP%	FP%	H-Index
China	630	24.56	62.06	37.94	88.41	47
USA	623	24.29	57.62	42.38	72.71	57
UK	230	8.97	46.15	53.85	59.13	44
Japan	192	7.49	54.17	45.83	75.52	30
Spain	174	6.78	65.52	34.48	85.06	24
Australia	168	6.55	46.43	53.57	71.43	41
Netherlands	146	5.69	41.78	58.22	60.96	35
Germany	109	4.25	39.45	60.55	65.14	26
Norway	109	4.25	32.11	67.89	54.13	33
Italy	76	2.96	56.58	43.42	76.32	17

TP: The total publications of a country; TP%: The percentage of the total publications; SP%: The percentage of publications of a country without international collaborations; CP%: The percentage of publication of a country with international collaborations; FP%: The percentage of first-author country publications. Articles originating from the Taiwan region were not included under the China heading for analysis; articles originating from England, Scotland, Ireland, and Wales were grouped under the United Kingdom (UK) heading. USA: United States.

3.3.2. Contribution of Institutions

Table 4 presents the main performance of the top 10 most productive institutions in the research field of input–output analysis during 1990–2017. Among the top 10 institutes, half came from China, and the rest came from Australia, Netherlands, the United Kingdom (UK), and Japan, respectively. This indicates that the institutions from China have played an increasingly prominent role in the research field of input–output analysis. Except for the Chinese Academy of Sciences and the National Institute of Environmental Studies, the others are all universities. The Chinese Academy of Sciences had the highest contribution, with 127 articles in terms of total publications, followed by the Beijing Normal University (87 papers) and the University of Sydney in Australia (87 papers). The University of Sydney also has the most total citations (3897 times) and the highest h-index (36). The University of Leeds and the University of Sydney rank first and second in terms of citations per publication. This indicates that the publications from these two institutes have relatively greater influence in the research field of input–output analysis, while the average citation per article in China is still relatively lower than other institutions. This reflects the gap between China and other international high-yield institutions in terms of the quality and influence of publications.

Table 4. Top 10 most productive institutions.

Institute, Country	TP (%)	TC	TC/TP	H-Index
Chinese Academy of Sciences, China	127 (4.95)	1950	15.35	25
Beijing Normal University, China	87 (3.39)	1030	11.84	16
University of Sydney, Australia	87 (3.39)	3897	44.79	36
Tsinghua University, China	68 (2.65)	1328	19.53	22
Peking University, China	61 (2.38)	1557	25.53	20
University of Groningen, Netherlands	56 (2.18)	1123	20.05	21
University of Leeds, UK	55 (2.14)	2500	45.45	28
National Institute for Environmental Studies, Japan	45 (1.75)	904	20.09	19
Beijing Institute of Technology, China	38 (1.48)	510	13.42	11
University of Maryland, USA	38 (1.48)	1182	31.11	16

TP: total publications; %: ratio of one institution's publications to total number of publications; TC: total citations; TC/TP: average citation per publication.

3.3.3. Contribution of Authors

The most active authors can also be called key authors. Table 5 presents the top 20 most productive authors in the field of input–output analysis between 1990–2017. The most prominent author regarding productivity is Lenzen from The School of Physics in The University of Sydney, who has published

50 articles. The second and third key authors are Guan from The University of East Anglia (36 articles) and Hubacek from The University of Maryland (35 articles). However, Peters, ranking 12th in the total volume of publications, has the highest average citation per publication (78.20). Su has published 18 articles with 1056 citations, which makes him rank second in terms of average citation per publication. This indicates that they are also influential authors in the field of input–output analysis.

Table 5. Top 20 most influential authors.

Author Name	Affliction	Country	TP	TC	TC/TP	H-Index
Lenzen, M	University of Sydney	Australia	50	2030	40.60	25
Guan, D	University of Leeds	UK	36	1719	47.75	19
Hubacek, K	University of Maryland	USA	35	1720	49.14	20
Wood, R	Norwegian University of Science and Technology	Norway	35	756	21.60	15
Liang, S	Tsinghua University	China	30	567	18.90	15
Chen, GQ	Peking University	China	28	1082	38.64	15
Hertwich, EG	Norwegian University of Science and Technology	Norway	27	1000	37.04	17
Santos, JR	George Washington University	USA	26	582	22.38	14
Feng, K	University of Maryland	USA	25	963	38.52	13
Suh, S	University of California, Santa Barbara	USA	22	775	35.23	15
Wiedmann, T	University of Sydney	Australia	21	1005	47.86	13
Nakajima, K	National Institute for Environmental Studies	Japan	20	419	20.95	13
Peters, GP	Norwegian University of Science and Technology	Norway	20	1564	78.20	15
Chen, B	Beijing Normal University	China	19	247	13.00	7
Nagasaka, T	Tohoku University	Japan	19	402	21.16	13
Nansai, K	National Institute for Environmental Studies	Japan	19	207	10.89	11
Kagawa, S	Kyushu University	Japan	18	211	11.72	11
Kucukvar, M	University of Central Florida	USA	18	377	20.94	11
Su, B	National University of Singapore	Singapore	18	1056	58.67	11
Dietzenbacher, E	University of Groningen	Netherlands	17	329	19.35	8

TP: the number of published articles in RCR; TC: the number of citations; TC/TP: the cites per article; Affiliation: where the author is working at the moment of publication.

3.4. Highly Cited Articles

Table 6 shows the most highly cited articles in the field of input–output analysis from 1990 to 2017, including the article's name, author(s), journal's name, the country of the first author, total citations, average annual citations, and publication year. It can be found that the authors of four articles are from Australia, three are from the United States (USA), two are from the United Kingdom (UK), and the rest countries appear only once. The indicators of total citations and average annual citations can help to evaluate the impact of publications. Among the input–output analysis-related articles published between 1990–2017, the most highly cited article is entitled "Growth in emission transfers via international trade from 1990 to 2008", which was published in The Proceedings of the National Academy of Sciences of the United States of America in 2011, and had 406 total citations and 58 annual citations. It is an international collaborative paper whose authors were from Norway, Germany, and the USA. Based on a trade-linked global input–output analysis, this article evaluates the CO_2 emission transfers via international trade during 1990–2008 in a quantitative way. The research concluded that the emissions in developed countries seem have stabilized, while in fact, their consumption-based emissions have growth faster than local emissions via international trade. This indicated that countries should pay more attention to the emission transfers via international trade, and evaluate the change in emissions from both a productive and consumption perspective [18]. "A modified ecological footprint method and its application to Australia", authored by Lenzen and Murray and published in *Ecological Economics*, ranked second in terms of total citations (288). By employing a single-region, static, partially closed input–output framework, it presented a new calculation of Australia's ecological footprint. The results indicate that the per-capita ecological footprint has a correlation with household expenditure, and that the ecological footprint decreases noticeably with household size [19].

Table 6. Top 15 most highly cited articles.

Article	Author(s)	Journal	Country	TC	TC/Y	Year
Growth in emission transfers via international trade from 1990 to 2008	Peters, GP.; Minx, JC.; Weber, CL; Edenhofer, O	Proceedings of the National Academy of Sciences of the United States of America	Norway	406	58	2011
A modified ecological footprint method and its application to Australia	Lenzen, M; Murray, SA	Ecological Economics	Australia	288	16.94	2001
Efficient input–output model representations	Rabitz, H; Alis, OF; Shorter, J; Shim, K	Computer Physics Communications	USA	279	14.68	1999
Methods for life cycle inventory of a product	Suh, S; Huppes, G	Journal of Cleaner Production	Netherlands	275	21.15	2005
Primary energy and greenhouse gases embodied in Australian final consumption: an input–output analysis	Lenzen, M	Energy Policy	Australia	269	13.45	1998
The drivers of Chinese CO_2 emissions from 1980 to 2030	Guan, D; Hubacek, K; Weber, CL; Peters, GP; Reiner, DM	Environmental Change-Human and Policy Dimensions Global	UK	263	26.3	2008
Optimal design of sustainable cellulosic biofuel supply chains: Multiobjective optimization coupled with life cycle assessment and input-output analysis	You, FQ; Tao, L; Graziano, DJ; Snyder, SW	Aiche Journal	USA	247	41.17	2012
Energy and carbon embodied in the international trade of Brazil: an input–output approach	Machado, G; Schaeffer, R; Worrell, E	Ecological Economics	Brazil	227	13.35	2001
Structural decomposition analysis applied to energy and emissions: some methodological developments	Su, B; Ang, BW	Energy Economics	Singapore	226	37.67	2012
Life cycle greenhouse gas (GHG) emission analysis of power generation systems: Japanese case	Hondo, H	Energy	Japan	225	17.31	2005
The carbon footprint of UK households 1990–2004: A socio-economically disaggregated, quasi-multi-regional input–output model	Druckman, A; Jackson, T	Ecological Economics	UK	216	24	2009
Quantifying the global and distributional aspects of American household carbon footprint	Weber, CL; Matthews, HS	Ecological Economics	USA	214	21.4	2008
Evaluating tourism's economic effects: new and old approaches	Dwyer, L; Forsyth, P; Spurr, R	Tourism Management	Australia	208	14.86	2004
Mapping the structure of the world economy	Lenzen, M; Kanemoto, K; Moran, D; Geschke, A	Environmental Science & Technology	Australia	198	33	2012

Year: publication year; Country: the country of the first author; TC/Y: Annual citations; TC: total citation.

3.5. Cooperation Network Analysis

There are numerous researchers around the world from different counties and institutions; it is possible to observe the social interaction and understand the organization of the scientific community of the IO analysis field through cooperation network analysis. In the cooperation network, the nodes can be countries/institutions/authors, and the links represent the collaboration relationship between them. This study focuses on the cooperation networks of key institutions and authors. In total, 53 institutions have published more than 15 papers in the field of input–output analysis. Among them, 52 institutions have collaborative relationships, and only the Linkoping Institute of Technology has no cooperation with other institutions in this field. Figure 3 visualizes the collaborative network of these 52 institutions. The largest cluster is consisted of 12 nodes, where the biggest node is the Chinese Academy of Science with 127 publications and 30 cooperation partners. The members in this cluster are mainly institutions from China. The second large cluster consisted of eight nodes. The largest node is The University of Sydney, which has 98 publications and 19 cooperation partners.

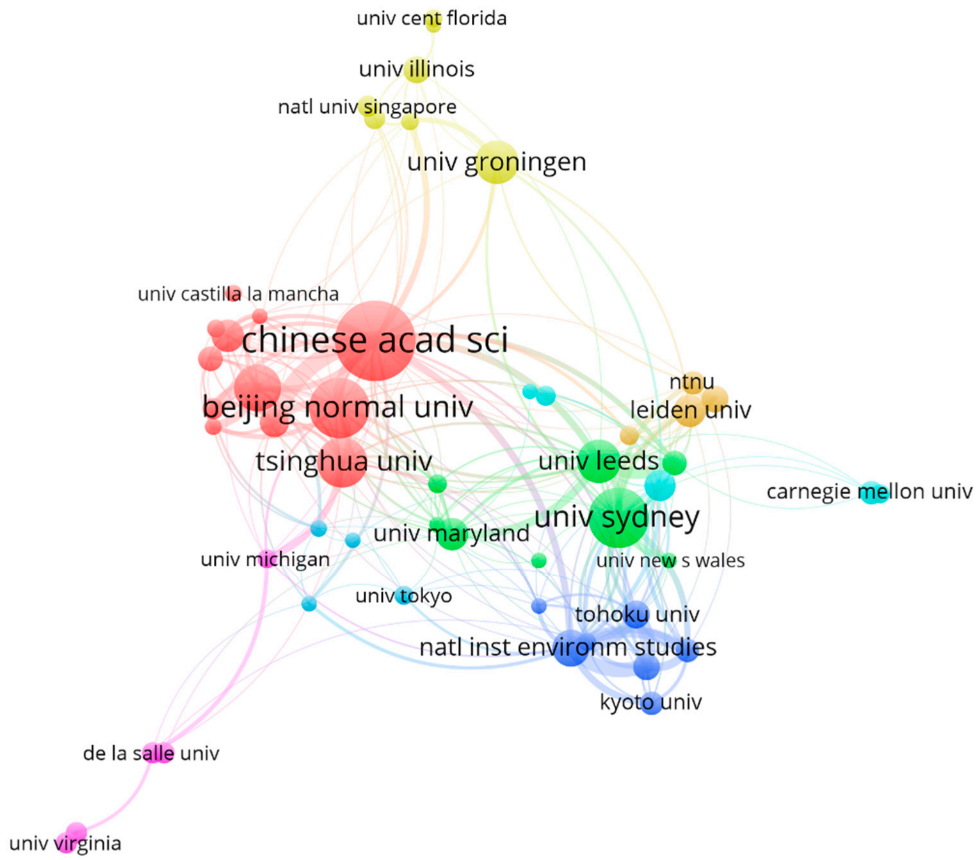

Figure 3. Institution collaboration network in the field of input–output (IO) analysis with a minimum threshold of 15 publications.

There are 48 authors publishing at least 15 papers in the field of input–output analysis. Figure 4 shows the largest subnetwork of 46 nodes and 176 links. The top high-yield authors have formed their own cooperative team. Among them, the largest node is Lenzen, who has 50 publications and 12 neighbors, and is followed by Guan, who has 36 publications and 12 partners. Meanwhile, Hubacek and Feng have the most close and frequent cooperation relationship. The authors in the subnetwork are divided into seven clusters in different colors. Both Cluster 1 and Cluster 2 have the largest number of members (12).

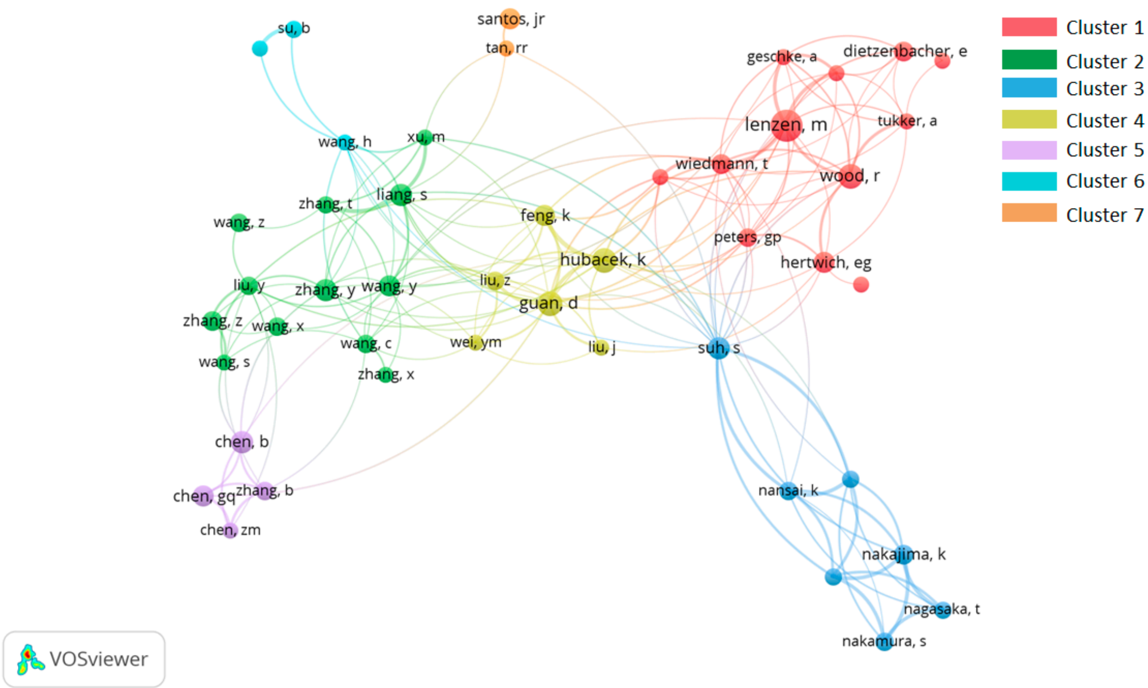

Figure 4. Author collaboration network in the field of IO analysis with a minimum threshold of 15 publications.

3.6. Bibliographic Coupling Analysis

Bibliographic coupling occurs when two documents share one or more references, which indicates that these two documents probably treat a related subject matter [20]. The higher the coupling strength of these two documents, the more references they share [21]. Bibliographic coupling analysis is able to explore the hidden relationships among articles and partly present the evolutionary pattern of the research frontiers in a specific topic [22]. Figure 5 illustrates the bibliographic coupling network with the citation threshold set as 40, which consists of 277 articles. These nodes are classified into seven clusters in different colors. By analyzing the papers in each cluster, the specific research focus of each cluster can be discovered. Table 7 lists the lead papers and summarizes the research focus for each of the seven clusters. The topical literature classification summarized in Table 7 shows that input–output theory has tended to focus on environmental impacts, footprint analyses (such as the water, carbon, or ecological footprint), and energy flow analysis. Especially, multi-region input–output (MRIO) has been developed to measure resource use and pollution generation embodied in the interregional and international trade flows [23]. Based on the environmental extended IO framework, many studies have investigated the driving forces of energy consumption and emission changes using structural decomposition studies. IO analysis is also referred as a tool to complement process-based life cycle assessment (LCA) to form a hybrid LCA approach, which has been the focus of research in the past 20 years [3,24]. In addition, according to the average publication year, it can be found that "carbon footprint" and "embodied emission" (Cluster 3) have attracted high attention and become research hotspots in recent years. Therefore, the primary insight that can be gained from this classification is the opportunity for additional research in the IO analysis field.

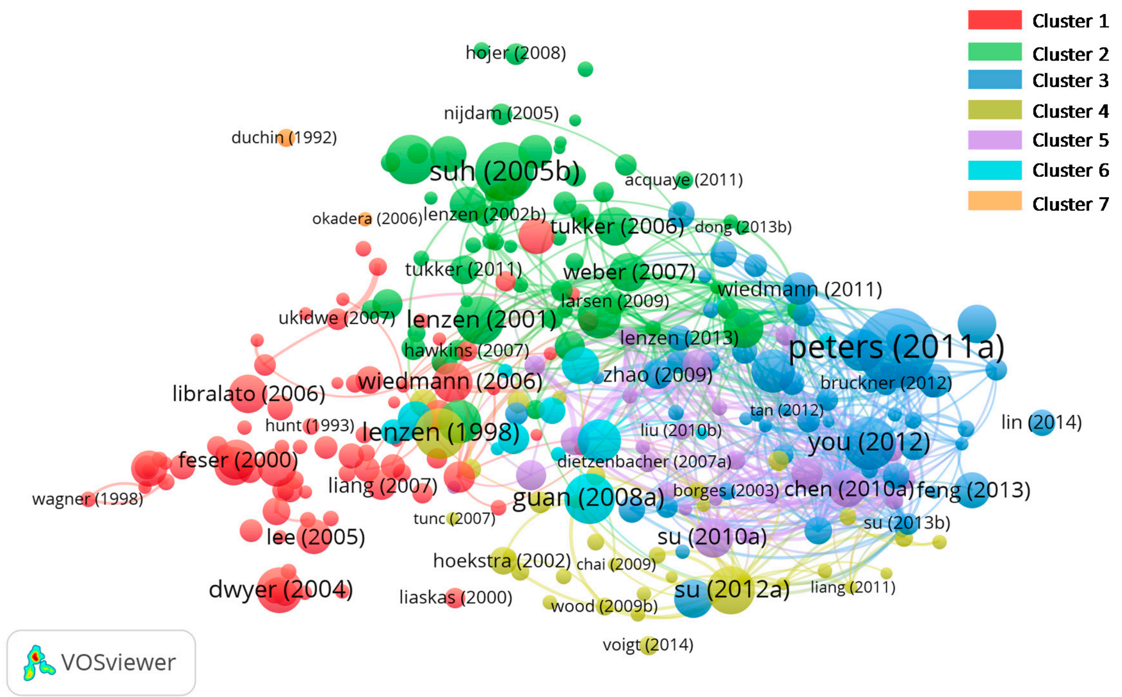

Figure 5. Bibliographic coupling network of IO analysis research field.

Table 7. Research topic and lead papers of each cluster.

Cluster #	No. of Paper	Area of Research Focus	Average Publication Year	Lead Papers in Terms of Total Link Strength
1	82	Ecological network, ecological footprints	2003	Wiedmann (2006) [25]; Turner (2007) [24]; Lenzen (2007) [26]; Hawkins (2007) [27]; Mcgregor (2008) [28]
2	62	Environmental impact, carbon footprint, multi-regional input–output model; hybrid life cycle assessment (LCA)	2007	Wiedmann (2009) [29]; Minx (2009) [30]; Hertwich (2011) [31]; Wiedmann (2010) [32]; Munksgaard (2005) [33]
3	59	Carbon footprint, embodied emission, input–output analysis	2012	Wiedmann (2011) [34]; Andrew (2009) [35]; Su (2013) [36]; Peters (2012) [37]; Kanemoto (2012) [38]
4	34	Structural decomposition analysis	2009	Liu (2010) [39]; Su (2012) [40]; Su (2012) [41]; Weber (2009) [42]; Wood (2009) [43]
5	24	Emission inventory, carbon emission	2010	Guo (2007) [44]; Chen (2010) [45]; Chen (2010) [46]; Su (2010) [47]; Serrano (2010) [48]
6	14	Environmental input–output, water footprint	2009	Druckman (2009) [49]; Lenzen (2011) [50]; Hubacek (2009) [51]; Guan (2008) [52]; Liu (2009) [53]
7	2	Industrial ecology, water pollutant	1999	Duchin (1992) [54]; Okadera (2006) [55]

3.7. Keywords Analysis

Keywords provide important information that reflects the core content of the articles. There are a total of 5168 author keywords in 2565 publications. After merging similar keywords (i.e., "biofuel" and "biofuels" are merged into "biofuel"), a total number of 4597 keywords were gained for further analysis. Among them, 3543 (77.07%) of them were used only once, and 475 (10.33%) keywords were used twice. This indicates a research focus dispersion and a lack of continuity. Furthermore, 381 (8.29%) keywords appearing more than three times, representing the main research streams of input–output analysis.

Table 8 lists the top 20 author keywords in this field. "Input–output analysis" is the most frequently (1148 times) used keyword without a doubt. "Multi-region input–output analysis" is the second most frequently used keyword. "China" ranks the third, which indicates that the economic and environmental issues in China have attracted great concern. The keywords' frequency change from 1990 to 2017 can be used to discover the evolution tendency of these studies, which can be divided into five periods. The rank of keywords' frequency has been changed greatly. For example, "carbon footprint" appeared after 2004, and become a hot topic due to global intense concern regarding climate change and carbon emissions. "International trade" and "industrial ecology" have gained greater attention since 2000. "life-cycle assessment" and "structural decomposition analysis (SDA)" are the key research methods combined with IO theory. By contrast, the rank of "economic impact" has declined.

Table 8. Top 20 most frequent author keywords.

Author Keywords	FR (%)	1990–1994		1995–1999		2000–2004		2005–2009		2010–2017	
		FR	R	FR	R	FR	R	FR	R	FR	R
Input–output analysis	1148 (24.97)	14	1	48	1	70	1	231	1	785	1
multi-region input–output analysis	169 (3.68)	0	-	0	-	1	48	7	13	161	2
China	141 (3.07)	0	-	1	27	1	48	14	6	125	3
carbon emission	123 (2.68)	0	-	2	13	3	8	9	12	109	4
life cycle assessment	110 (2.39)	0	-	0	-	11	2	21	2	78	6
structural decomposition analysis (SDA)	91 (1.98)	0	-	1	27	1	48	7	13	82	5
industrial ecology	90 (1.96)	0	-	0	-	2	13	15	5	73	7
international trade	78 (1.70)	0	-	0	-	6	3	11	10	61	8
economic impact	67 (1.46)	2	2	2	13	4	4	17	3	42	10
carbon footprint	63 (1.37)	0	-	0	-	0	-	7	13	56	9

FR (%): Frequency of occurrences and its percentage; R: rank in different periods.

The co-occurrence network of high-frequency keywords (frequency more than 10) was visualized and clustered in Figure 6 to discover the theme cluster. The keywords' co-occurrence network consisted of 101 nodes and 914 links. It provides a useful indication of the main topics within the input–output analysis research field. According to the cluster results in VOS Viewer, 10 clusters vary in size and partially overlap. The detail research topics for each cluster are summarized in Table 9. Some clusters mainly focus on its wide application, such as, greenhouse gas (GHG) emissions (Cluster 1), embodied emissions in international trade (Cluster 4), water footprint and virtual water (Cluster 6), or agriculture and biofuel (Cluster 8). Meanwhile, some clusters investigate the methodology combination; for example, Cluster 2 focuses on evaluating the regional economic impacts of various policy measures based on IO tables and the CGE model; Cluster 3 mainly utilizes the hybrid LCA method and structural path analysis; the literature in Cluster 5 is mainly based on material flow analysis (MFA) and LCI; Cluster 9 studies urban metabolism based on a physical input–output table and network analysis; and in Cluster 10, material requirements planning (MRP) theory is applied to combined with IO analysis and Laplace transforms for the economic evaluation in multi-level or multi-stage production inventory systems. Thus, IO analysis can also be applied to processes on the company level.

Table 9. Research topic clusters of IO analysis field based on author keywords.

Cluster #	No. of Nodes	Research Topics
1	21	Structural decomposition analysis, GHG emissions, embodied energy, environmental impact
2	17	Input–output analysis, economic impact, CGE, uncertainty, linear programming
3	13	Industrial ecology, ecological footprint, hybrid LCA, environmental input–output analysis, trade, structural path analysis
4	10	Multi-region input–output analysis, international trade, carbon footprint, embodied emission

Table 9. *Cont.*

Cluster #	No. of Nodes	Research Topics
5	9	Material flow analysis, energy consumption, environment, life cycle inventory
6	9	China, water footprint, virtual water, water scarcity
7	8	Life cycle assessment, sustainability, consumption, economic input-output
8	6	Energy, employment, agriculture, biofuel
9	5	Network analysis, physical input–output table, ecological network analysis, urban metabolism
10	3	Supply chain, Laplace transform, material requirements planning (MRP)

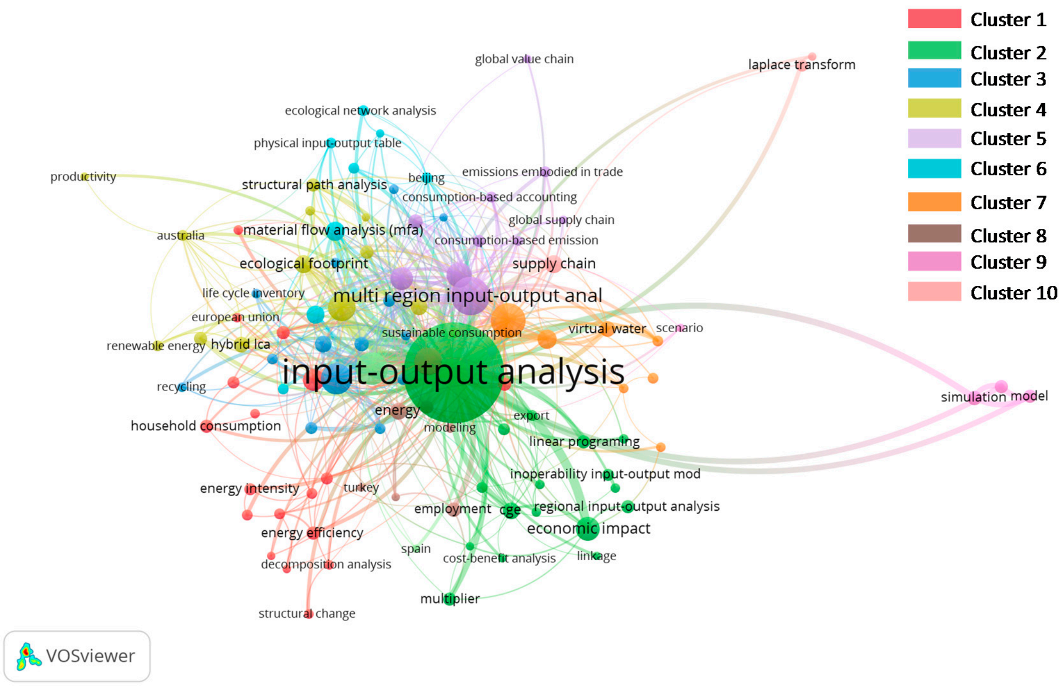

Figure 6. Keyword co-occurrence network in the field of IO analysis.

4. Conclusions

In this study, bibliometric analysis technology is developed to characterize the input–output analysis-related literature during the period of 1990–2017 based on the Science Citation Index and Social Sciences Citation Index databases. Bibliographic coupling analysis and keyword analysis are conducted to discover the evolution pattern of the research frontiers in the IO analysis field. Recently, the issues regarding environmental impacts and carbon/water/ecological footprint have increasingly received more focus, while the traditional economic impact analysis has gained less attention. The MRIO model has been extensively applied to measure resource utilization and pollution generation embodied in interregional and international trade flows, especially since the increased level of discussion surrounding carbon leakage and carbon responsibility distribution against the global climate change background. In addition, in terms of research methods, IO table/analysis is widely combined with other theories (e.g., CGE, MFA, LCI, and MRP theory) for more holistic and comprehensive analyses. The integration of different methods can help researchers deal with different and complex problems that cannot be handle by single method.

Through retrieving the SCI and SSCI databases and manual screening, 2565 articles in English were collected for bibliometric analysis. The results are indicated as follows. Firstly, the number of total publications in this field grew steadily in the early stage, from 1990 to 2003; in addition, with the growing concern for the environment and the development of environmental extended IO analysis, more and more papers were published from 2004 to 2017. Secondly, from a country point of view, China and the USA are the top two most active countries with large numbers of publications in this field. Especially, China has enjoyed rapid growth, and even surpassed the USA to rank first currently. The Chinese Academy of Sciences, Beijing Normal University, and The University of Sydney are top three most productive institutions, and The University of Leeds, with a high number of citations per publication, also has great influence in the research field of IO analysis. Thirdly, it is found that the top 15 journals contribute approximately 44% of the total publications in the IO analysis-related field, where The Journal of Cleaner Production was the most productive journal, followed by Ecological Economics and Energy Policy.

This study can be seen as a snapshot of the IO analysis-related research from 1990 to 2017, which could help researchers gain the interesting and meaningful information from abundant bibliometric data quickly. For example, the identified highly cited articles may prove a good starting point. Carefully monitoring the work of influential scholars in this field may provide some guidelines for future research. Identifying the mainstream journals may be useful when researchers choose to publish their studies in a proper channel. However, there are still some limitations in this study. (i) There are opportunities for a more detailed and in-depth analysis on the research gaps and future research directions. For example, meta-analysis is a statistical approach that combines the results from multiple studies in an effort to increase power (over individual studies) and improve the estimates of the size of the effect and/or resolve uncertainty when reports disagree. (ii) The data used in this study was collected from the WoS database, and the scope of data sources could be expanded to the studied selection of any language and other citation information, such as Scopus and Google Scholar, in the future. Further studies should mitigate these limitations.

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