Bibliometric and Social Network Analysis of Civil Engineering Sustainability Research from 2015 to 2019

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Abstract: With the development of civil engineering sustainability, the scope of corresponding research covers a broader range. It is difficult for researchers to master the holistic situation of the study, leading to duplication and lag of their research. Therefore, this paper aims to present a state-of-the-art of the research of civil engineering sustainability by adopting two new methods (bibliometric and social network analysis) to review the literature of this field. It is concluded that the existing research takes engineering as the main subject to improve its sustainability through technologies. Current research mainly focuses on technological innovations and evaluations of environmental impacts in the fields of construction technology, energy consumption, material preparation, and design. The countries with the largest number of published articles are the United States and China. The Hong Kong Polytechnic University is the institution that has published more articles than others. Journal of Cleaner Production and Sustainability are the journals that have published the most articles. For the researchers, a professor of the University of Adelaide is the researcher who has published the most articles, and experts from South China University of Technology, Chongqing University, and University of Brighton are the main hubs among different researchers.

Keywords: civil engineering; sustainability; bibliometric; social network analysis; relation matrix

1. Introduction

Sustainable development has become the theme of the times. Civil engineering is in urgent need of sustainable development due to its large environmental impacts and resource consumption [1]. The results of research have indicated that the construction sector is one of the major contributors to environmental impacts [2]. With the continuous deepening of civil engineering sustainability research, it is necessary for researchers to conduct an overall analysis of the research status, providing support for subsequent research. It can be found that it is difficult to analyze the main points of existing research through traditional literature reviews because the number of related articles is very large, the scope of this field is very broad, from the analysis of the sustainability of civil engineering. In order to promote the sustainable development of civil engineering, researchers have carried out a lot of research work in various fields in civil engineering, such as sustainable buildings [3], bridges [4], road constructions [5], and sustainable materials [6].
For the research on the sustainability of buildings, researchers have focused on the operation period of buildings, which has prompted the comparison of different green building standards [7], sustainable energy technologies [8], and ventilation strategies [9]. Additionally, the research of comprehensive analysis about sustainability has gradually penetrated the construction of buildings. Some researchers established life cycle assessment (LCA) models of building construction from three aspects: environment [10], economy [11], and society [12]. For the construction of prefabricated buildings, the environmental impacts of three different concrete floor slabs have been quantified [13]. In order to improve social abilities of buildings, stakeholder analysis [14] was adopted in some projects. Then, the social life cycle assessment framework of different stakeholders has been established and analyzed based on the production of prefabricated building components [15]. With the deepening of research, the scope of the sustainability of buildings has been extended to the production of sustainable concrete [16,17], maintenance [18], and refurbishment [19] of buildings. After the independent study of various dimensions of building sustainability, comprehensive sustainability assessment received much more attention, especially building construction [20]. According to López, there are 101 methods of sustainability assessments in current research, which could be classified into 36 typical methods [21]. Some sustainability evolution methods have been established for urban centers [22] and existing buildings [23].

For bridge engineering, Shekhar et al. [24] concentrated on life cycle cost under chloride exposure conditions. O’Born [25] compared two schemes of a bridge in Norway and found that the wooden bridge has better environmental benefits. Navarro et al. [26] pointed out the important role of life cycle design of bridges in social impact. Du et al. [27] used eight bridges to analyze the different environmental impacts between concrete bridges and soil-steel composite bridges. After research of the construction period, Pang et al. [28] compared four different strength methods from the environmental perspective. Moreover, Zhang et al. [29] conducted a quantitative study on the uncertainty of environmental impact during operation. The methods to assess the sustainability of bridges were proposed by Arya et al. [30] and Yadollahi et al. [31].

As to road construction, the application of sustainable materials is the most important part. Balaguera et al. [32] reviewed the application of LCA in alternative materials for road construction and concluded that the most common materials are recycled asphalt, fly ash, and polymer. Recycled materials like rubber [33], steel slag [34], recycled asphalt [35], recycled concrete [36], and fly ash [37] have attracted growing studies. The most widely used sustainable materials are fly ash concrete and recycled aggregate concrete. Xu and Shi [38] summarized the performance of fly ash concrete, including chemical performance, durability, and sustainability. Based on the statistical analysis of over 200 articles about fly ash concrete, Hemalatha and Ramaswamy [39] analyzed its application status, material performance, existing problems, and put forward the classification suggestions of fly ash. Wang et al. [40] established a method to evaluate the life cycle sustainability of fly ash concrete and Zhang et al. [41] considered the uncertainty of carbon emissions for fly ash concrete. For recycled aggregate concrete, Dimitriou et al. [42] and Guo et al. [43] discussed the influence of the quantity of bonding mortar and the quality of original concrete in durability. Zhang et al. [44] summed up the results of LCA about recycled aggregate concrete. With regard to sustainable materials, researchers mainly focus on LCA databases and the production of suitable sustainable materials. Martínez-Rocamora et al. [45] reviewed the LCA database of building materials in the world and pointed out that the Gabi, Ecoinvent, and the US Athena databases showed great integrity and availability.

Through the review of current research on sustainability of civil engineering, it can be found that existing research has covered the whole fields of civil engineering. However, the existing articles of literature review represent that the reviewers could only focus on part research areas due to the limitations of the existing methods, which makes it difficult for researchers to grasp the overall view and link their research with the whole trend of civil engineering sustainability research, resulting in repeat and lag research, while the research of the articles in Environmental Impact Assessment...
Review [46], sustainable decision-making [47], and green building [48] proved that the bibliometric analysis and the social network analysis (SNA) are effective methods to comprehensively analyze the existing research by constructing the literature relationship map from the perspective of the basic statistics and mutual relations of the literature research contents, even if there are a lot of relevant articles in this research filed.

Bibliometrics is a quantitative analysis method of literature by applying mathematical and statistical methods [49], it can extract valuable information from massive literature data by statistical analysis of research fields, publications, countries, institutions, etc., and provide crucial support for subsequent research. As to the SNA, it is a quantitative and visual analysis method developed by sociologists based on mathematics and graph theory, which has been widely used in engineering construction [50], international trade [51], and knowledge management [52]. The SNA can use centrality analysis to study the nodes and connections of networks from a new perspective through the establishment of actors, ties, and boundaries [53].

Geng et al. [54] analyzed the articles of building life cycle assessment from 2000 to 2014 based on bibliometric analysis. The research of Yin et al. [55] showed that bibliometric analysis and knowledge network could effectively discuss the literature about building information modeling (BIM) and off-site construction. Cabeza et al. [56] carried out comparative analysis between the databases Web of Science (WoS) and Scopus in the energy efficiency and climate impacts of buildings through bibliometrics. Oraee et al. [57] studied BIM-based Construction Networks as an example to quantitatively evaluate different research contents by the network analysis and bibliometric. Through the scientometric study of 501 off-site construction documents, Hosseini et al. [58] found the complement of existing research and indicated the importance of operation and management. Li et al. [59] made a bibliometric analysis of 1874 BIM articles and determined the corresponding crucial research areas and clusters. Ganbat et al. [60] concentrated on the BIM risk management by reviewing 526 articles based on a database, Citespace, with the bibliometric method. Udomsap and Hallinger [61] selected 2877 Scopus-indexed documents to study the hotspots of sustainable construction through bibliometric review and network analysis. In recent years, bibliometrics was employed to analyze the evolution of prefabricated building policies by Wang et al. [62].

Through the analysis of relevant research, it is found that the bibliometric analysis has been applied in the literature research of civil engineering, especially in the research of BIM. Due to the development of library management, bibliometric analysis has been integrated into different databases, such as WoS and Scopus. This phenomenon makes it possible to carry out important statistics and citation analysis in civil engineering literature research, and conduct further study through the Citespace.

However, the SNA is still in the development stage in the analysis of civil engineering literature, and current applications mainly based on three different softwares: (1) the direct visualization analysis method of articles in different databases based on VOSviewer; (2) literature data analysis method based on traditional network analysis tools such as the Pajek; (3) network visualization analysis of literature based on Gephi (an open source free cross-platform network analysis software based on java virtual machine) and text-processing. After comparing the three methods, it is found that Gephi has been widely adopted due to its advantages of visualization and data analysis.

Therefore, this paper will conduct an in-depth quantitative analysis in the research of civil engineering sustainability from 2015 to 2019 based on the SNA (applying Gephi) and bibliometric analysis. According to the statistical result of articles, this paper firstly discusses the research directions, source publications, source countries, and institutions. Then, two network models of research contents and teams are constructed separately based on the co-occurrence frequency relationship among different keywords and authors. The quantitative results of the influences of different research contents and researchers are calculated through the SNA. At last, the research hot points, methods, deficiencies, and the relationships among authors of existing research are presented.
2. Collection of Basic Data and Bibliometric Research of Civil Engineering Sustainability

The purpose of this study was to conduct a comprehensive analysis of civil engineering sustainability research to identify the hotspots and shortcomings of existing research, providing reference for future needs and directions through integration of international literature published during the past five years (2015–2019). The research process mainly included three parts: (1) determination of the basic data source of published literature; (2) establishment and preliminary statistics of the network model of the published articles; (3) systematic analysis of the established network. Figure 1 shows the main roadmap of the analysis process of the paper.

![Diagram](image)

**Figure 1.** Analyzing roadmap of civil engineering sustainability research based on the social network analysis (SNA).

In the process shown in Figure 1, some information needed for bibliometrics could be preliminarily obtained through the export of science citation index (SCI) and social sciences citation index (SSCI) journal literature data related to civil engineering sustainability. After artificial adjustment and research of existing data, the bibliometric analysis could be carried out to determine the statistical results of research fields, publications, source countries, and institutions. According to the preliminary statistical database, the co-occurrence relationship matrices of keywords and authors could be constructed based on the common occurrence frequency of keywords and authors in different literature. Then, this research imported the above matrices into Gephi to construct a research network and cooperation network to calculate the centrality, eigenvector centrality, and betweenness centrality of the networks.

2.1. Data Collection for Civil Engineering Sustainability Research

The selection of reliable and representative civil engineering sustainability research literature was the basis for the establishment of the network research. Since sustainability is a comprehensive integration of multiple dimensions of technology, economy, environment, and society, in order to ensure data quality, this paper selected two parts in the core database of WoS as the search sources: (1) Science Citation Index Expanded (SCI-EXPANDED); (2) Social Sciences Citation Index (SSCI). In order to retrieve literature related to the sustainability of civil engineering in the selected database, it was necessary to choose retrieval terms for two topics (civil engineering and sustainability): (1) civil engineering is a general term for the construction of various types of projects, including buildings, bridges, tunnels, roads, etc.; 22 search terms were adopted for the retrieval; (2) sustainability includes three pillars: environment, economy, and society; this section selected 13 search terms for the retrieval. Table 1 shows the selected terms of the two topics. The keyword search field in the WoS was set as the title in order to ensure that the search results were related to the research.
A total of 2751 articles published in 2015–2019 were collected by searching (from January 2015 to October 2019, a total of 2697 journal articles and 54 conference papers). After literature retrieval, there were three steps for article confirmation: (1) read the title of the literature, confirm whether the literature is based on civil engineering, and study its sustainable performance (including energy saving, material saving, management, etc.); (2) on the basis of the title, the journal was scrutinized to confirm whether it is a journal of sustainable or civil engineering related; (3) if both of the above conditions were met, but still could not be confirmed, read the abstract to confirm whether it is an available document. From the selection of articles, there were 1846 articles (including 1826 journal articles and 20 conference papers) which were identified that really conducted civil engineering sustainability research selected as the basic database after in-depth screening of the 2751 articles searched. The reliability and representativeness of the civil engineering sustainability research database were guaranteed to lay a foundation for the network and bibliometric analysis through the selection of basic articles.

2.2. Analysis of Civil Engineering Sustainability Research Based on the Bibliometric

This paper separately analyzed the research directions, source publications, source countries, and source organizations of published articles from 2015 to 2019 based on the basic literature database of civil engineering sustainability.

2.2.1. Analysis of the Research Directions of Civil Engineering Sustainability

In civil engineering sustainability research, there are 65 different research directions provided by the basic statistics in the WoS from 2015 to 2019 (the distribution of research directions is shown in Figure 2). The four research directions of “Engineering”, “Environmental Science Ecology”, “Science Technology—Other Topics”, and “Construction Building Technology” are relatively more focused than others, exceeding 10% of the overall articles. It can be seen that over a quarter of the research is engineering-related.

![Figure 2. Distribution map of sustainability research direction of civil engineering during 2015–2019.](image-url)
2.2.2. Analysis of Source Publications of Civil Engineering Sustainability

In the source publications, all the 1846 articles were published in 330 different journals or conferences with an average impact factor (IF) of 4.19. There were 445 articles which were published in journals with an IF bigger than 5. The number of articles published in journals with IF bigger than 4 was 865. Moreover, the most influential article was published in *Nature Materials* (IF: 38.663). The basic statistical results of the top 15 source publications could be seen in Table 2, which contains 1036 articles (56.12% of total articles).

**Table 2. Statistics on source publications of the top 15 journals.**

| No. | Journal                                                   | No. of Articles | Percent | IF 2019 |
|-----|-----------------------------------------------------------|-----------------|---------|---------|
| 1   | Journal of Cleaner Production                            | 268             | 14.52%  | 7.246   |
| 2   | Sustainability                                            | 196             | 10.62%  | 2.576   |
| 3   | Energy and Buildings                                     | 96              | 5.20%   | 8.467   |
| 4   | Construction and Building Materials                      | 84              | 4.55%   | 4.419   |
| 5   | Building and Environment                                 | 67              | 3.63%   | 4.971   |
| 6   | Sustainable Cities and Society                           | 63              | 3.41%   | 5.268   |
| 7   | Renewable and Sustainable Energy Reviews                 | 46              | 2.49%   | 12.11   |
| 8   | International Journal of Life Cycle Assessment           | 45              | 2.44%   | 4.307   |
| 9   | Resources Conservation and Recycling                     | 34              | 1.84%   | 8.086   |
| 10  | Journal of Building Engineering                          | 33              | 1.79%   | 3.379   |
| 11  | Structure and Infrastructure Engineering                 | 32              | 1.73%   | 2.62    |
| 12  | Energies                                                 | 21              | 1.14%   | 2.702   |
| 13  | Applied Energy                                            | 18              | 0.98%   | 8.848   |
| 14  | Proceedings of the Institution of Civil Engineers        | 17              | 0.92%   | 1.063   |
| 15  | Journal of Construction Engineering and Management       | 16              | 0.87%   | 2.347   |

It can be observed from the results that *Journal of Cleaner Production* and *Sustainability* were the most attractive journals to publish civil engineering sustainability articles over the past five years. In the journals listed in Table 2, there are nine journals that are the top 10% journals of their own fields in Journal Citation Reports, such as *Renewable and Sustainable Energy Reviews* (IF:12.11) which contained 67.36% articles published in the top 15 journals, representing the fact that civil engineering sustainability research has a relatively high impact. From the results in Table 2, we can recognize that most of the journals are related to sustainability, energy utilization, and renewable materials. However, some important journals focusing on the mechanical properties of civil engineering, such as *Construction and Building Materials*, have begun to publish some sustainable-related literature. This phenomenon shows that sustainability has a considerable impact on traditional civil engineering research.

2.2.3. Analysis of Source Countries and Institutions of Civil Engineering Sustainability

It was found that 1546 institutions in 89 countries or regions have studied civil engineering sustainability from 2015 to 2019 through the analysis of collected literature. The United States and China are the countries with the largest number of relevant publications, with 30.17% of the total articles published. The aggregated results of the source countries and institutions could be seen in Figures 3 and 4. As can be seen in Figure 3, the percentage of the published articles in the top 15 countries accounts for 92.23% of the total articles. That is to say, almost all the studies of civil engineering sustainability are based on the research results of the above regions. Among them, the United States is the country with the largest number of articles published, with 295 articles (15.98%) published, while China, ranked second, has published 262 articles (14.19%). Over the past five years, the number of articles published by the Hong Kong Polytechnic University (HKPU) was far higher than that of other institutions, reaching 48. Among the institutions with 1% of the total number of publications, 75 articles (4.06%) were published by two institutions in China (HKPU, Hong Kong University), and 41 articles were published by two institutions in Spain (UPV, Universidad Politécnica de València;
UPC, Universitat Politècnica de Catalunya). It is worth noting that the Vilnius Gediminas Technical University (VGTU) in Lithuania published 23 articles related to the sustainability of civil engineering during the past five years, ranking fifth in the general institutions.

![Figure 3. Percentage of articles published in different countries or regions.](image)

![Figure 4. Institutions that published over 1% of the selected articles. Note: IIT: Indian institution of technology (Indian); CNRS: Centre national de la recherche scientifique.](image)

2.3. Establishment of Network Model of Civil Engineering Sustainability Research and Cooperation about Authors Based on Co-Occurrence Frequency

2.3.1. Establishment of Network Model of Civil Engineering Sustainability Research Based on Co-Occurrence Frequency

The keywords are the concise technical terms of articles, which can effectively reflect the theme of texts [63]. A co-occurrence relationship matrix can be formed by counting the frequency of the occurrence of different keywords in the same articles [64]. The matrix can represent the distance between two different themes. Then the keywords network could be constructed and analyzed.

There were 7315 different keywords in the selected 1846 articles according to the statistics of keywords frequency. Among them, the number of keywords that appeared in more than or equal to 5, 10, and 20 articles are 609 keywords, 276 keywords, and 151 keywords, respectively. In order to present the results better, this paper focused on the analysis of keyword networks with frequency more than or equal to 20. The selection basis was as follows: (1) in the fields of knowledge management [65], BIM [57], and prefabricated construction [58], 20 is often used as the threshold of a network division in key research areas; (2) after conducting a network analysis under different thresholds (frequencies of keywords over 5 and 10), the network with the frequencies of keywords more than or equal to 20 can demonstrate existing research much better than others. Then, we took the number of
co-occurrences of 7315 keywords in 1846 articles as the strength of the relationship among different keywords. The relationship matrix of the overall network could be constructed based on strength among different keywords.

Then, a network model of civil engineering sustainability research based on the co-occurrence matrix could be established. There was no normalization of the co-occurrence frequency of the keywords, considering that the establishment of this network was mainly based on the co-occurrence frequencies of keywords. This paper separately established and analyzed the social network model of the overall keywords network and the keywords whose frequency was more than or equal to 20 with the relationship matrix. The overall network model can be seen in Figure 5 that was established through the co-occurrence relationship of 7315 keywords in 1846 articles.

![Figure 5. The social network model of civil engineering sustainability (Gephi, Nodes = 7315, Edges = 225,741).](image)

All the 7315 keywords were divided into different groups based on the degree and the strength of their connections among keywords. The different colors in Figure 5 mean the groups determined by modularization (grouping was conducted according to the relationships among keywords, which is irrelevant to the meaning of texts). The size of the node name is the degree of the indicator. As can be seen from Figure 5, the green module with “Engineering” as the core and the purple module with “Science & Technology” as the core were the most influential and extensive parts in the network. After counting the frequency of the keywords, it was found that there were 5338 keywords whose frequency was only one. These one-time keywords make such a wide range of keywords as “Engineering” prominent, and it was difficult to find the analysis core of the existing research. Therefore, we no longer analyzed the network characteristics of the overall keyword network.

A keyword network model with frequency more than or equal to 20 was constructed based on the co-occurrence relationship of 151 keywords in 1846 articles, see Figure 6. Like the overall network, the size of node name represents the degree of the indicator. It can be found that the core research fields in the study of civil engineering sustainability were highlighted with the increase of keyword frequency requirements. The research fields were mainly divided into three different modules including the purple module with “Engineering”, the green module with “Environmental Science & Ecology”, and the blue module with “Environmental Science".
Figure 6. The network model of civil engineering sustainability with frequency of keywords more than or equal to 20 (Gephi, Nodes = 151, Edges = 11,882).

2.3.2. Establishment of Cooperation Network Model of Civil Engineering Sustainability Based on Authors’ Cooperation

The SNA of the authors can clearly reveal the cooperation relationship among authors, building a concrete data foundation for the subsequent research work. This paper conducted statistics and analysis on the cooperation network of civil engineering sustainability research over the past five years based on the analysis of collaboration among authors in the basic database. Through the statistics of the database, a total of 4814 authors have conducted a series of studies in these fields, of which 3892 authors have only appeared once, and 599 authors have only appeared twice. The number of authors who have published over five articles is only 99. In order to avoid the influence of too many authors in an article and individual authors on the cooperation network, we established the relationship matrix based on the top five authors in an article, and excluded individual authors and groups (group size accounting for less than 0.5% of total authors) in the network. The cooperation network of research teams can be seen in Figure 7.

As can be seen from Figure 7, the cooperation network in civil engineering sustainability study from 2015 to 2019 is mainly divided into 10 different small groups, among which J.Zuo (University of Adelaide) and E.K. Zavadskas (VGTU) are the most influential authors in the overall center map. There are five research groups that have established contacts through the authors, called communicators, who play important roles in connecting authors in different groups.
3. Analysis of Civil Engineering Sustainability Research Based on Social Network

Based on the network model of civil engineering sustainability research, the core research content in the existing research could be identified. At the same time, the relationship among the research groups was analyzed through the SNA of cooperative network. Then, the key researchers (core researchers and communicators) in the group could be identified.

3.1. SNA of Civil Engineering Sustainability Research Network

By conducting the overall network analysis and the centrality analysis of civil engineering sustainability research network from the perspective of relationship among existing research contents, it is found that the keywords with frequency less than five mainly appear in conjunction with “Engineering”, which has a great impact on the network structure and integrity analysis. Therefore, the network analysis of civil engineering sustainability research in this paper mainly relies on the network model whose frequency of keywords is more than or equal to 20.

3.1.1. Whole Network Analysis of Civil Engineering Sustainability Research Network

In order to reflect the whole characteristics of the existing civil engineering sustainability research, the whole network density and network distance were adopted to analyze the model. The whole network density refers to the ratio of the actual number of connections to the maximum number of connections in the network, the network distance refers to the calculated mean of the average distance of each node in the network. The whole network density and network distance are mainly to represent the degree of whole network connection from the perspective of network tightness, and to reflect the degree of connection between network indicators.
Through dichotomizing and numerical calculation, the overall network density and average distance of the civil engineering sustainability research network with keywords frequency greater than or equal to 20 were calculated. The results show that the overall network density reaches 0.6206, and the average distance is only 1.379. It shows that there is a close relationship among these 151 different research contents. Most of the research contents have been studied in the same articles, and few of those that have not established links can be connected through short indirect links. Overall, the research core of the existing civil engineering sustainability research is very clear, and the cross-study of the 151 research contents is quite sufficient.

3.1.2. Centrality Analysis of Civil Engineering Sustainability Research Network

Centrality is an important indicator of the network analysis, which includes two parts: centrality and central potential. They quantify the core degree of the node and the closeness of the network respectively. The eigenvector centrality was selected to be calculated, because the purpose of the centrality analysis was to identify the core nodes (research contents).

The eigenvector centrality measures the importance of the node from the number and the importance of neighbor nodes. The advantage of this feature is that it can consider the importance of the related objects on the basis of the correlation number of the research contents, and avoid the influence of partial edge research contents.

The results of the eigenvector centrality were calculated based on the network of civil engineering sustainability research, as shown in Figure 8. Table 3 lists the top 30 calculations of the eigenvector centrality (EC).

![Figure 8. The eigenvector centrality of civil engineering sustainability network.](image)

It can be seen from Table 3 that “Engineering”, “Science & Technology”, and “Sustainability” are the core research contents of civil engineering sustainability, that is, the existing research still uses scientific and technical means for sustainable optimization in engineering. The research ideas are basically consistent with traditional research. The eigenvector centrality result of “Engineering” was 0.478, which is 2.03 times of the figure of “Sustainability”. In terms of research directions and methods, “Environmental Sciences” and “Construction & Building Technology” are the main concerns of existing research, and their influences are about 78.03% and 53.14% of that of “Engineering”. Energy consumption is also an important research direction, whose impact is 32.01% of the maximum result. LCA has received extensive attention because of its ability to quantify environmental impacts, its impact reaching 30.54% of the maximum result, which is 3.84 times that of life cycle cost (LCC). Social-LCA has not entered the 151 key research areas due to too few studies. With the in-depth development of green concept, more and more attention has been paid to sustainable design. The influence of “Design” has reached a maximum of 25.73%, there is still a large space for it to rise in
the future. Concrete, which is one of the most used materials in civil engineering, has a great impact on sustainable material, with the figure reaching 27.2% of the maximum result. For the regions about civil engineering sustainability, China has become the most important place for researchers. From the statistic results about frequency of keywords, China is the only country that appears in Table 3, ranking 38. The eigenvector centrality result of China was 0.047, ranking 32nd. The reason for this phenomenon is not only the excessive number of researchers in China, but also that the construction in China is much larger than that of other countries, which has led researchers in other countries to also take projects in China as cases to study.

Table 3. Partial results of eigenvector centrality of the civil engineering sustainability research network.

| No. | Keyword                          | EC  | No.   | Keyword                        | EC  |
|-----|----------------------------------|-----|-------|--------------------------------|-----|
| 1   | Engineering                      | 0.478 | 16    | Life-Cycle Assessment          | 0.123 |
| 2   | Science & Technology—Other Topics| 0.373 | 17    | Materials Science              | 0.106 |
| 3   | Environmental Sciences           | 0.263 | 18    | Durability                     | 0.084 |
| 4   | Ecology                          | 0.263 | 19    | Buildings                      | 0.08  |
| 5   | Construction & Building Technology| 0.254 | 20    | Management                     | 0.078 |
| 6   | Sustainability                   | 0.235 | 21    | Impact                         | 0.076 |
| 7   | Performance                      | 0.197 | 22    | Optimization                   | 0.073 |
| 8   | Environmental Sciences & Ecology | 0.183 | 23    | Systems                        | 0.069 |
| 9   | Construction                     | 0.179 | 24    | System                         | 0.068 |
| 10  | Energy                           | 0.153 | 25    | Model                          | 0.067 |
| 11  | Life Cycle Assessment            | 0.146 | 26    | Emissions                      | 0.062 |
| 12  | LCA                              | 0.133 | 27    | Mechanical-Properties          | 0.061 |
| 13  | Energy & Fuels                   | 0.132 | 28    | Framework                      | 0.061 |
| 14  | Concrete                         | 0.13  | 29    | Strength                       | 0.061 |
| 15  | Design                           | 0.123 | 30    | Embodied Energy                | 0.059 |

On the whole, the core of existing civil engineering sustainability research is to use the scientific and technical means to conduct sustainable assessment or optimization in engineering. Existing research still pays more attention to the construction process and energy consumption, but more research has been carried out on sustainable design. At the same time, environmental impacts have attracted too much attention, while little attention has been paid to the economic and social dimensions.

3.2. SNA of Cooperation Network

There are 4814 authors who have studied the sustainability of civil engineering during the past five years, according to the statistical results. The analysis of the cooperation network can quantify the influence and communication abilities of different authors.

Here, the degree centrality and betweenness centrality were used as metric indicators for analyzing the authors’ influence and communication ability.

3.2.1. Degree Centrality of Cooperation Network

The eigenvector centrality is characterized by the characterization process, which eliminates the effect of small groups. The analysis of author cooperation network focuses on the small groups in the whole author network, so this paper selected the degree centrality to analyze the influences of different authors.

The calculated results of the degree centrality (DG) can be seen in Table 4 based on the author cooperation network. Because we mainly focused on the influences of different authors, only the top 10 authors are listed.
Table 4. Degree centrality results of author cooperation network.

| No. | Author  | DG    | Institution                     | No. | Author    | DG    | Institution                     |
|-----|---------|-------|---------------------------------|-----|-----------|-------|---------------------------------|
| 1   | J.Zuo   | 48    | University of Adelaide          | 5   | J.Kim     | 25    | Sungkyunkwan University          |
| 2   | E.K.Zavadskas | 38       | VGTU                            | 5   | M.Z.Jumaat | 25    | Universiti Malaya                |
| 3   | V.W.Y.Tam | 27      | Western Sydney University        | 8   | R.D.Chang  | 23    | Bond University                  |
| 4   | S.Lasvaux | 26      | University of Applied Sciences & Arts Western Switzerland | 9   | X.L.Zhang  | 22    | City University of Hong Kong     |
| 5   | J.Santos | 25    | University of Twente            | 10  | Y.F.Wang   | 21    | Beijing Jiaotong University      |

As can be seen from Table 4, Professor J.Zuo of the University of Adelaide is the core author of the existing author’s cooperation network. In the top 10 authors, only 2 authors are from the institutions included in Figure 4. The main reason for this phenomenon is that most researchers engaged in civil engineering sustainability research regard sustainability as a small part or accessory of civil engineering mechanical properties or engineering applications, which leads to the lack of systematic analysis in civil engineering sustainability research. With the increasing importance of sustainable development, researchers need to focus more on sustainability, rather than as an accessory of mechanical research.

3.2.2. Betweenness Centrality of Cooperation Network

It can be found that the author cooperation network shows a good betweenness centrality in the connection of different groups. The results of the betweenness centrality (BC) are shown in Table 5, which lists the top 20 authors. This paper uses No.B to represent the ranking results of the betweenness centrality. In order to reflect the comparison results, the ranking results of the degree centrality (No.D) are also listed in Table 5.

Table 5. The betweenness centrality results of cooperation network about civil engineering sustainability.

| No.B | No.D | Author      | BC     | No.B | No.D | Author      | BC     |
|------|------|-------------|--------|------|------|-------------|--------|
| 1    | 24   | R.Y.Jin     | 24,454 | 11   | 39   | W.Pan       | 7876   |
| 2    | 1    | J.Zuo       | 21,783 | 12   | 59   | Y.Wang      | 7763   |
| 3    | 62   | H.Y.Li      | 20,349 | 13   | 2    | E.K.Zavadskas | 6722 |
| 4    | 22   | M.Skitmore  | 17,963 | 14   | 134  | W.Y.Szeto   | 6288   |
| 5    | 47   | Q.Chen      | 14,768 | 15   | 3    | V.W.Y.Tam   | 6240   |
| 6    | 33   | Y.Liu       | 13,995 | 16   | 13   | J.Y.Wang    | 5819   |
| 7    | 52   | C.Koo       | 11,985 | 17   | 124  | Y.Jiang     | 5565   |
| 8    | 121  | C.Mao       | 11,613 | 18   | 9    | X.L.Zhang   | 5511   |
| 9    | 6    | J.Kim       | 10,891 | 19   | 16   | S.Kim       | 5445   |
| 10   | 173  | J.Wang      | 7905   | 20   | 93   | H.Adeli     | 5158   |

It can be seen from Table 5 that there is a big difference between the degree and betweenness results. R.Y.Jin and J.Zuo are the most influential authors in connecting different groups. As core researchers in the groups, they have established direct contacts with other groups, making them have higher orders. However, some authors show a high betweenness centralities and low degree centralities, such as H.Y.Li, C.Mao, J.Wang, W.Y.Szeto, Y.Jiang, and H.Adeli. This illustrates that although the six authors are slightly less involved in scientific research in groups, they are important contacts within the groups or between groups. These authors play an important role in the study of civil engineering sustainability research and in promoting communication among different research groups.

Through the analysis of Figure 7 and Table 5, it can be found that there are few direct cooperative studies among the authors who published a large number of articles. However, through the exchanges between scholars, most of the research teams have established cooperative links and carried out cross
research. It is found that the cooperation among research teams is greatly influenced by the openness of their countries.

4. Discussion

Today, civil engineering is facing the severe challenge of sustainable development. The whole life cycle of civil engineering includes material production, design, construction, operation and maintenance, demolition, and reuse, which makes it difficult for traditional research to comprehensively analyze. However, the whole civil engineering research can be systematically analyzed through the social network and other information processing technologies from the point of view of a complex system.

As to the bibliometric results, we found that “Engineering”, “Environment”, and “Construction Technology” played a vital role in existing research. That is to say, the current research on civil engineering sustainability still focuses on the realization of engineering sustainability through technological breakthroughs. The practicability in engineering is still the center of current research, and there is relatively little research focusing on sustainability or sustainable assessment. This result can also be found in the follow-up analysis of journals, countries, and institutions. Most of the articles selected focused on construction, energy-saving, material production technology. For the definition of civil engineering sustainability, the comprehensive assessment or improvement analysis in three dimensions of sustainability is relatively less.

As to the civil engineering sustainability research network, it can be seen that “Environment” was the most important part among the three dimensions of sustainability in the past five years, the number of studies of “Economy” was relatively less. However, the research on “Society” dimension was the most insufficient in the past five years, which is in urgent need of a large amount of targeted analysis. In engineering and material technology research, design was also a very important research direction in recent years, in addition to construction and energy saving technology. Many experts have realized the key role of design in the life cycle of project, so the importance of design is relatively high in current research of sustainability.

As to the cooperation network, it can be seen that there were mainly 11 large research teams with certain degree of correlation in recent five years. Among the 10 authors in the center, four authors come from the countries between the Tropics of Cancer and Capricorn. Four other authors come from countries or regions with small land areas that are greatly affected by climate change. This phenomenon represents that the degree of local climate change has certain impacts on research of civil engineering sustainability. For example, the government of Switzerland promulgated the Carbon Dioxide Emission Reduction (Draft) in 2007, which led to geographers and meteorologists analyzing the melting of local glaciers very early and indirectly promoting the development of sustainable research in civil engineering. In the betweenness analysis, the important authors who played the role of communication among different research teams were identified. Due to the communication skills, these researchers were more likely to form new achievements with cross research nature, which should be paid more attention in future research.

5. Conclusions and Outlooks

This paper analyzed 1846 published articles on the theme of civil engineering sustainability based on the bibliometric and SNA. Through the study of the keyword co-occurrence and research teams, the research cores, research contents, source publications, countries and institutions of existing civil engineering sustainability research were analyzed. The quantitative assessment of influences on different contents was carried out. The main conclusions were as follows: (1) the existing research of civil engineering sustainability took engineering as the main subject to study through technology, and the coupling of environmental science and engineering technology was sufficient; (2) the main contents were to conduct technological innovations and evaluations of environmental impacts on construction technology, energy consumption, material preparation, and design; (3) the existing research mainly focused on the environmental dimension of sustainability, but lacks sufficient attention
to the economic and social dimensions; (4) in the research object, many researches took the engineering
cases of China as examples, making China and Hong Kong appear as keywords in many articles; (5) in
the source publications, the average IF of journals is 4.19, 24.11% of articles were published in journals
with an IF greater than 5. *Journal of Cleaner Production* and *Sustainability* are the two most frequently
published journals; (6) in the source counties and institutions, USA and China are the counties with the
largest number of relevant researches in the world, and the HKPU is the institution with the largest
number of published articles; (7) of the researchers, Professor J.Zuo of the University of Adelaide is the
researcher who has published the most articles in civil engineering sustainability, and researchers such
as H.Y.Li, C.Mao, J.Wang, and W.Y.Szeto are the bridges among different researchers or research groups.

From the analysis of this paper, we can recognize that bibliometrics and SNA are the effective
methods to evaluate and quantify the researches and examine publication characteristics, such as
research contents and teams, institutions, and journals. The two methods provide a quantitative
perspective to understand the characteristics associated with civil engineering sustainability research.
Based on these two methods, the hotspot of research and the main hub of research teams were identified,
presenting useful references for researchers to select the field and direction of future research about
civil engineering sustainability. Moreover, the relationship of different research teams was revealed.
This could be a direct basis for communications among researchers.

In addition to the conclusions mentioned above, there are still some limitations and contents
to be further studied. As to the limitations, there are three major limitations in the current research:
(1) the scope of this paper was limited to the past five years; (2) the quantitative results of the SNA are
difficult to form a universal benchmark because of the lack of relevant research; (3) the automation
level of this method is still very low. In order to solve the above problems, some research should be
carried out in future. First, further research could consider the articles published in other periods.
Moreover, the evolution trend of research about civil engineering sustainability should be analyzed
based on the literature database in future research. Then, in order to improve the efficiency of literature
analysis, more attention should be paid to how to establish an automatic identification technology
of civil engineering sustainability research based on artificial intelligence methods. On the basis of
existing SNA, we can further deepen network analysis technology, integrating super network and
complex network into the analysis methods, and gradually improve the depth of literature analysis.

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