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Highlights

- Comprehensive bibliometric study to celebrate forty years' contribution of Computers & *Chemical Engineering (CCE).*
- Identification of the leading topics, authors, institutions, and countries using WoS database.
- Analysis of the publications of CCE with bibliometric indicators.
- Mapping of the publications by using the VOS viewer software.

Forty Years of Computers & Chemical Engineering: A bibliometric analysis

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Abstract

Computers & Chemical Engineering (CCE) is one of the premier international journals in the field of chemical engineering. CCE published its first issue in 1977 and completed forty years in 2016. More than four decades of continuous and successful journey influenced us to celebrate its contribution through a comprehensive bibliometric study. Using the Web of Science Core Collection database we depict trends of the journal in terms of papers, topics, authors, institutions, and countries. Networks visualization of co-citation of journals and authors, bibliographic coupling institutions and countries, and co-occurrence of author keywords are prepared using the visualization of similarities (VOS) viewer software. The present analysis explores publication and citation patterns of the journal. Professor Ignacio E. Grossmann, Carnegie Mellon University, and USA respectively appear as the most productive and influential author, institution, and country in CCE publications. Optimization based research topics received most attention in CCE publications.

Keywords: Bibliometrics; journal; Computers & Chemical Engineering; Web of Science; VOS viewer.

1. Introduction

The journal of Computers & Chemical Engineering (CCE) was established in 1977. The primary aim of this journal is to publish new findings in the application of computing and systems technology to chemical engineering problems. The journal's emphasis is put on new findings within various major areas, including: modelling, mathematical programming, cyber infrastructure, intelligent systems, process dynamics and control, abnormal events management, plant operations, enterprise-wide management and domain applications. It welcomes different types of research papers to cover different aspects including new applications of established methods, comparisons of methodologies, demonstrations of state-of-the-art industrial applications and noteworthy improvements in computation for training and education. CCE also welcomes general research papers on emerging new issues and topics. CCE publishes full-length articles, reviews, short notes and letters to the editor. Richard R. Hughes was the founding editor-in-chief of the journal along with Charles H. Ware, who acted as the editor of the special feature algorithms and programs. Richard R. Hughes edited CCE for 11 years until his death. In the inaugural editorial, Prof. Richard R. Hughes described the intention of the journal. The journal was created to provide the platform for new developments in the application of computers to chemical engineering problems. E.N. Pistikopoulos of Texas A&M University is currently working as the editor-in-chief and the editorial board is completed by four editors: J.H. Lee of Korea Advanced Institute of Science and Technology, A.B.P. Póvoa of Instituto Superior Técnico, V. Venkatasubramanian of Columbia University, and F. You of Cornell University and one associate editor: A. Mitsos of RWTH Aachen University. From the very beginning, the outstanding contributions and dedication of its editors have made this journal a success. The journal is now indexed in all well-established databases including Science Citation Index (SCI), Scopus, Current Contents, Engineering Index. According to Scopus, CCE has a CiteScore 3.98 in 2018. As per Journal Citation Reports from Clarivate Analytics the journal has an impact factor 3.334 and 5-year impact factor 3.373 in 2018. The Eigenfactor® and Article influence of CCE in 2018 are 0.011 and 0.609, respectively. In 2018, the journal recorded a total of 1129 submissions and 318 papers were accepted for publication. During last five year the journal has consistently shown an acceptance rate around one third of submissions, which proves its efficiency in editorial processes.

In 2018, CCE completed its forty two years' journey. This study aims to examine the performance of the journal during those years. More specifically, its aim is to discover the consequence, productivity and influence of CCE in new research findings in the application of computers to chemical engineering problems. A general bibliometric study is used to classify statistical information of its publications and then to analyze its performance. Bibliometric studies use a procedure to measure the quality of scientific information using different qualitative as well as quantitative indexes. Library and information sciences provide the basic concepts of bibliometric study. Ideas from computer science and statistics have helped to advance its methodological and data processing procedures. This type of study is useful in surveys, reviews and big data analysis. It is commonly used to analyze influence of a topic in literature, contribution of a journal in a particular discipline, tribute to legends, contribution of an institution and a country. For instances; Bornmann et al., (2015) use bibliometric study to measure contributions of different countries; Linton, (2004) uses this type of study to quantify contributions of universities; and Merigó et al. (2018) use the study to measure contributions of journals. Bibliometric studies are also common to use in the analysis of a topic based research works. Merigó et al., (2019a) and Laengle et al., (2018) presented a bibliometric analysis to measure performances of universities on Production & Operations Management (POM) and Operations Research and Management Science (OR-MS) respectively. Using a bibliometric study, Kazemi et al., (2018) analyzed research publications on reverse logistics and closed-loop supply chain published in the International Journal of Production Research. Examples of some notable topics based bibliometric studies are: natural resource (Zhong et al. 2017), innovation (Merigó et al. 2016), fuzzy research (Blanco-Mesa, Merigó and Gil-Lafuente, 2017), sustainability (Franceschini et al. 2016), etc. In early years, citation analysis was the main reputed tool to identify influential journals in a particular discipline. Generally, scientific journals have some explicit objectives, aims and scopes. Journals publish research works to fulfil their aims which in turn helps to enhance scientific understanding and innovations. Journals oftentimes modify their aims and scopes due to the ever changing scientific environment. Occasionally, it is useful to reassess performance of a journal during its journey. Bibliometric study can help to re-examine a journal's performance. The trends to revisit journals' performance in their important anniversaries have started more than three decades ago. In 1986, Hech and Bremser (1986) demonstrated sixty years' publication details of the journal The Accounting Review and analyzed its performance. Later in 2008, Weiss and Qiu (2008) investigated the publication outline of The Journal of Risk and Insurance to celebrate its platinum jubilee. There are several examples from almost all well-established publishers which used bibliometric studies to reassess performance of their journals during their significant anniversaries (Please see table 1).

Table-1 illustrates journals from six well-established publishers including Elsevier, Springer, Wiley, Emerald, Taylor & Francis and World Scientific which analyzed their publications during their important anniversaries. Four journals in table 1 (Information Sciences, Transportation Research Part A, Quality & Quantity, European Journal of Marketing) celebrate their half century through bibliometric studies. Four well-established journals from Elsevier analyze their journey of four decades. During the last decade this type of studies have increased a lot due to easily accessible data from sources like Web of Science, Scopus, and Google Scholar. Zhang et al. (2019) used different text mining techniques to analyze all CCE publications for the period of 1977 to 2017. The present article differs from Zhang et al. (2019) in many aspects. Using computing technology, Zhang et al. (2019) presented a topic analysis of the published articles in CCE while the present article uses the bibliometric methods to explore exclusively publication pattern, citation structure, most cited articles, leading authors, institutions and countries. Moreover, the present article presents the network visualizations of the bibliographic coupling among countries and institutions, co-citation among the journals & authors, and co-occurrence of keywords of all the CCE publications.

The purpose of the present bibliometric study is to celebrate the four decades of CCE and analyze all articles published in this journal from 1977 to 2018. Its aims are to reveal the most influential and contributing authors, universities and countries in CCE publications. The study intends to analyze publication and citation details, highly cited articles, and collaborations among the authors, institutions and countries. Moreover, it divulges analysis of bibliographic coupling (Kessler, 1963) among the countries and institutions, co-citation (Small, 1973) of journals & authors, and co-occurrence of keywords in the CCE publications. More specifically, this work intends to answer the following questions. During the journey since 1977, what is the publication and citation pattern of CCE? Which publications and issues have received high attention? Which authors, institutions and countries contribute the most? Which authors, universities, and countries receive the highest number of citations in the publications of CCE? Which journals have close links with CCE? In the published research in CCE, which universities and countries are involved in collaborative works? Which keywords are most often used in the publications? The aim of this study is not only to find answers to the above questions but also celebrate the journal's achievements. The study commemorates the contribution of the editors, authors, institutions, and countries during the forty years journey of the journal. It also provides entire information of the publications of the journal, which will be helpful to the young researchers for their future research planning. Moreover, it will be helpful to the editors of the journal to assess those topics which have the most potential and which, in turn, may help to decide future strategies of the journal.

Remaining parts of the paper are arranged as follows. The second section discusses the method of the study. Section 3 demonstrates details of publication pattern, citation structure, and most often cited articles, leading authors, institutions and countries of CCE. Section 4 presents a discussion with the network visualizations of the bibliographic coupling among countries and institutions, co-citation among the journals & authors, and co-occurrence of keywords. Final section summarizes the key conclusions of the work.

2. **Methods**

Data collection is an important part of a bibliometric study. Details of each CCE publication from 1977 to 2018 are accessed from the Web of Science (WoS) core collection database. Presently, there are several databases of scientific publications including Scopus, Google Scholar and WoS. In this study, we use the WoS core collection database and Scopus due to their reliability and easily accessible citation data. WoS is a modified form of the first ever scientific publication and citation databank, the SCI (Science Citation Index). Institute of Scientific Information (ISI) established the SCI database. Later, Thomson and Reuters took the ownership of this database and presently it is owned and managed by Clarivate Analytics. WoS has six citation indexes which are: Science Citation Index Expanded, Social Sciences Citation Index, Arts & Humanities Citation Index, Emerging Sources Citation Index, Book Citation Index, and Conference Proceedings Citation Index. WoS provides more than 100 years coverage of more than 18,000 journals, 180,000 conference proceedings, and 80,000 books. WoS offers several different types of data which are necessary to depict and measure performance of CCE including the number of publications, number of citations, most contributing authors and countries, most frequently discussed topics, and linking among those topics. Although WoS has a long successful history as an authenticate data source but recently Scopus emerges significantly to complement the WoS. The list of the most cited papers is updated using the database Scopus. Moreover, list of the most influential authors is prepared using the Scopus citation data. We have captured citation data using the Scopus database up to April 2020.

Collected data from WoS are classified and presented based on several bibliometric indicators including total number of publications (TP), total number of citations (TC), H-index, citation per paper (C/P), and different citation thresholds (250, 100, 50, 25, 10, 5 and 1 citations). TP and TC are the two basic indicators used for assessing the overall volume and impact of scientific publications. Both H-index and C/P offer further, more granular information on the journal publications' impact. The indicator TP gives information about number of publications which is necessary to analyze publication pattern and depict productive authors, institutions, and countries. TC is a well-established, purely citation based indicator to measure quality of scientific papers. It is useful to acknowledge and trace the original source and authorship of a concept or an idea. The C/P indicator captures average citations per paper and it is useful in comparative studies. H-index is a matrix representation of the indicators TP and TC. If an author has an H-index of h, it means that h publications of that author have received at least h citations or more (Hirsch, 2005).

In this review we use the visualization of similarities (VOS) software (Van Eck and Waltman, 2010) to prepare network visualization of bibliographic coupling (Kessler, 1963) of institutions and countries, co-citation (Small, 1973) of authors & journals, and co-occurrence of keywords used by the authors in the papers published in CCE. The focus on the analysis of bibliographic coupling, co-citations, and co-words is not only to explore the bibliographic connections among the authors, institutions, journals and countries but also to find those topics that are most often used by authors in the papers published in CCE. Bibliographic coupling analysis provides information on closely linked institutions and countries in CCE research. Two institutions/countries are said to be bibliographically coupled if they are jointly involved in research works. Two documents receive a point in the co-citation index when both the documents are commonly referenced by a third document (Small, 1973). Co-occurrence of author keywords explores frequently and concurrently used research topics in the papers published in CCE.

3. Results

CCE started its journey in 1977 with the 100 pages inaugural issue. The inaugural issue consisted of seven original articles, two short communications and one review article. The opening volume of CCE had three issues. Each year starting from 1978 up to 1982, i.e., from the 2nd to the 6th volume, it published four issues in each volume. From the 7th volume (1983) to the 11th volume (1987), it published six issues per year. From the 12th volume (1988) to the 27th volume (2003) the journal published 12 issues per year. From 2004 to 2006 the journal published two volumes in each year and all of those volumes had 12 issues. Next five years, i.e., from 2007 to 2011, it again released one 12 issued volume in each year. From 2012 to 2018, it published twelve volumes per year. “Steady-state cascade simulation in multiple effect evaporation” authored by G. Stewart (Heriot-Watt University), and G.S.G. Beveridge (University of Strathclyde), was the very first research article published in this journal. The first review article entitled “Analysis of a complex plant-steady state and transient behaviour” written by V. Hlaváček from the Institute of Chemical Technology was published in the first issue of volume one. Next sub-section analyzes year wise publication and citation structure of CCE.

a. Publication and citation structure of CCE

According to the WoS Core Collection search engine, from 1977 to 2018, CCE has published a total of 7226 documents. The search engine also discloses that the publications of the journal have received a total of 144011 citations up to 31st December, 2018. Figure 1 presents the number of papers published annually in the journal since 1977.

The publication pattern of CCE is increasing during the first two decades. Figure 1 displays that annual number of publications increased remarkably in the period of 1996 to 2000. Annual number of publications drops sharply in 2001 compared to its previous year and that pattern continued up to 2003. Annual number of publications improves in the next two years but it falls again in 2006 and 2007. After the year 2010, annual numbers of publications in CCE are consistently higher than two hundred. It shows the largest number of published papers in the year 1996 with 385 publications followed by the year 2000. WoS database confirms that 7226 documents of CCE have a total of 144011 citations. To assess the citation pattern of the journal, collected data are summarized and organized in an year-wise pattern and is presented in Table 2. Table 2 demonstrates citation related information of the publications of CCE for several categories including TP, TC, and citation thresholds including more than one, five, ten, twenty, fifty, one hundred and two hundred citations.

CCE published a total of 427 papers, 42.7 papers per year on average, during its first ten years. Thirteen papers among those 427 papers have more than one hundred citations. Note that, the number of publications in the year 1979 is 77, which is more than three times of the number of publications in the previous year. The journal published 1643, 2298, and 2228 articles in the second, third, and fourth decade respectively. The journal published 310 and 320 articles in 2017 and 2018 respectively. The journal got a total of 7522, 36156, 59397, and 39573 total citations from the publications in the first, second, third, and fourth decade respectively. Figure 2 presents pie diagram of distribution of citations over the four decades.

Publications during the third decade that is from 1997 to 2006 received the highest number of citations, which makes more than 40 per cent of the total citations of CCE. Publications received an average of 17.62, 22.01, 25.85, and 17.76 citations per paper published during the first, second, third, and fourth decade. The 238 papers published in the year 2004 got 9704 citations and it is the highest citation receiving publication year for CCE. Note that, six papers of 2004 have more than 250 citations and these six papers are also listed in the fifty most influential documents of CCE. Numbers of citations in the most recent years are low due to limited time for their accumulation. Figure 3 presents graphical representation of the number of articles with citations above several specified thresholds.

Around nine per cent of articles have not yet received any citation up to 31st December, 2018. Note that, the last year (i.e. 2018) has 200 documents out of the total of 654 documents which have not been cited yet. If we exclude the publications of the last two years, then 94.5 per cent documents of CCE have at least one citation. 54 publications have more than 200 citations and 200 publications more than 100 citations. More than two thirds of the documents have more than 5 citations. 3431 documents of CCE are in the i10 index club, i.e., these documents have at least ten citations. Next sub-section discusses fifty most cited papers published in the journal.

b. Influential papers in CCE

The present sub-section discusses those research papers which have received the largest number of citations. Table 3 presents fifty most cited research papers published in CCE with their respective TC, title, name of the authors, and the average citation rate per year.

The research work entitled “A Plant-Wide Industrial-Process Control Problem” jointly written by J. J. Downs, & E. F Vogel, has received the largest number of citations and tops the list in table 3 according to the WoS data up to 2018. Downs and Vogel (1993) developed an industrial chemical process model for benchmarking process control technologies. The developed model in the leading article can be fitted for both the multivariable control and plant-wide control problems. The review article entitled “A Review of Process Fault Detection and Diagnosis Part I: Quantitative Model-Based Methods” written by V Venkatsubramanian, R Rengaswamy and K. Yin is in the second position in the Table 3. Note that, this document received most citation according to the Scopus citation data. This document also has been receiving most citations per year on average. Venkatsubramanian et al., (2003) presents a high quality review on the quantitative model-based scientific methods applied in the process fault detection and diagnosis area; its direct relation with highly relevant industrial problems helps it to gain a high rate of acknowledgement from other researchers. The article entitled “Model Predictive Control: Past, Present and Future” (Morari and Lee, 1999) presents a comprehensive literature review of model predictive control and it is the third in the list with 989 citations. Morari and Lee, (1999) pointed out research gaps in subject areas including system identification, state estimation, monitoring and diagnostics. Moreover it overviewed many important practical and theoretical problems in the MPC framework. The fourth article in Table 3 is again a review paper which has 813 citations. Note that, this is the third part of the series of review papers on Process Fault Detection and Diagnosis. Each of the top nine articles has more than 500 citations. Most of the top ten articles are review of the state-of-the-art type. Seventeen articles out of the top 50 are focused on optimization. Besides the review works on optimization, there are also several papers on different types of optimization including “Simultaneous-Optimization” “Structural Optimization”, “Global Optimization”, “Dynamic Optimization”, and “Multi-objective Optimization”. Fourteen articles from Table 3 discussed different types of models which include “Quantitative Model”, “Simultaneous-Optimization Models”, “Dynamic Modeling”, “Adaptive Data Modeling” , “Model Predictive Control”, “Generic Model Control”, “Models For Refinery Operations”, and “Simultaneous-Optimization Models”. There are six documents in Table 3 from the year 2003 which appears as the most productive year in terms of highly cited articles. The year 1998 is the second most productive year with 5 documents in the list of 50 most cited documents. Figure 4 shows the distribution of the 50 most cited documents over the years.

Please note that, twenty three out of the top 50 most cited documents were published during the period of 1995 to 2005. The paper entitled "Biomass-To-Bioenergy and Biofuel Supply Chain Optimization: Overview, Key Issues and Challenges" (Yue et al., 2014) is the youngest paper in Table 3 (in the 48th position) with the third highest citation rate per year on average. The 30th paper entitled "Optimal Water Allocation in a Petroleum Refinery" (Takama et al., 1980) is the oldest paper in Table 3. Thirty influential papers have more than three hundred citations and twenty among them have more than 250 citations. Note that, Table 3 has six such articles which are receiving more than 50 citations per year on average. From Table 3 one may easily observe that state-of-art and review based research articles are the most often cited and are heavily represented. Next table presents 40 of the articles which have been most frequently cited in the papers published in CCE.

The article, Kondili et al., (1993), entitled "A general algorithm for short-term scheduling of batch operations—I. MILP formulation" published in CCE has a comfortable lead over the rest in Table 4. The research ideas demonstrated in Kondili et al., (1993) have been used and referenced in 177 documents of CCE. Note that, Kondili et al., (1993) has a total of 679 citations and it is placed in the fifth position in Table 3. The book published in the McGraw-Hill Chemical Engineering Series, entitled "Conceptual Design of Chemical Processes" and authored by James Douglas (Douglas, 1988), is listed in the second place. Kondili et al., (1993) and Douglas, (1988) have 144 and 91 co-citations respectively with the CCE publications. Four papers have more than one hundred co-citations with CCE. Geoffrion, (1972) is the oldest paper in the list. It was published in the 'Journal of Optimization Theory and Applications'. According to WoS, 99 documents published in CCE referenced Geoffrion, (1972) and as per Google Scholar it has more than two thousand two hundred citations. Figure 5 presents chronological visualization of the most cited documents in CCE.

In Figure 5 one can see that sixteen documents out of the forty most cited documents in CCE publications were published between 1985 and 1990. Top eight documents of Table 3 have been referenced in more than one hundred documents of CCE. The top 40 most cited documents by the CCE publications comprise ten books and thirty articles. Note that Table 4 lists 12 documents published in CCE and eight articles from AIChE J. The outcome shows close connection between CCE and AIChE J. The following sub-section reveals top authors, institutions and countries of CCE.

c. Leading authors, institutions and countries

This part of the manuscript is dedicated to those authors, institutions and countries who have contributed most to CCE's collection of articles. Table 5a acknowledges fifty most productive authors and ranks them according to their number of CCE publications. In addition, the Table captures other relevant information about the leading authors including their affiliations, TC, H-index, C/P and citation thresholds. Note that, TC, TP, H-index, C/P and citation thresholds of the authors are prepared solely on the basis of their publications in CCE.

Ignacio E. Grossmann of Carnegie Mellon University tops Table 5a with more than two hundred publications. Ignacio Grossmann is the most influential author of the journal as he leads in three basic categories TP, TC and H-index with a huge margin in comparison to the other listed authors. Note that, ten articles of Professor Grossmann have also been listed in the 50 most cited documents of CCE (see Table 3). Stratos Pistikopoulos of Texas A&M University is listed in the second position with 98 publications. Lorenz T. Biegler of Carnegie Mellon University who has 97 publications in CCE is closely following Stratos Pistikopoulos. Note that only six authors in Table 4 have more than fifty citations per paper. I. Grossmann again leads in the C/P index closely followed by Christodoulos A. Floudas and Venkat Venkatasubramanian. C. Floudas and V. Venkatasubramanian have four and three papers, respectively, in the list of 50 most cited documents of CCE (see Table 3). Note that, 48 documents of V. Venkatasubramanian accumulated a total of 2867 citations and the top three among them, which are listed in Table 3, have received a total of 2495 citations. I. Grossmann and C. Floudas have thirty four and fifteen documents, respectively, with more than 100 citations. Leading 50 authors contributed 63.5% of the published documents with more than 100 citations. USA based authors are in the top three positions and dominate the Top 50 list with a total of twenty two. The Top 50 list of authors is completed by twenty seven members from different European countries and only one Asian author.

Table 5b orders the top fifty influential authors based on the number of citations received by their CCE papers. Note that, table 5b is totally prepared based on the Scopus citation data up to April 2020. I.E. Grossmann tops Table 5b with 16370 citations followed by V. Venkatasubramanian with 5855 citations. Note that, V. Venkatasubramanian is in the 10th position in table 5a. R. Rengaswamy of Indian Institution of Technology (Madras) and S. N. Kavuri of Purdue University are in the fifth and sixth positions in this table although they do not get a position in the table 5a. There exist sixteen such authors in table 5b who are not in table 5a. USA leads table 5b with twenty-eight authors followed by the UK. Now, we will extend the analysis from author to the institution basis with Table 6 presenting the most productive and influential institutions in CCE.

Table 6 provides information on fifty most productive and influential universities in CCE. It gives information on country, citation structure, ARWU and QS ranking of these Top 50 institutions. Carnegie Mellon University from the USA leads the ranking in Table 6 followed by Imperial College London from the UK. Note that the significant contributions of two authors: Ignacio E. Grossmann and Stratos Pistikopoulos from the Carnegie Mellon University, who have contributed 206 and 98 papers respectively. Four authors (Nilay Shah, Constantinos Pantelides, Sandro Macchietto and John Perkins) from the Imperial College London are also listed in the top fifty leading authors of the CCE and their contribution helps the Imperial College London to achieve the second position in Table 6. European institutions are dominating Table 6 with twenty six representatives. Top 50 has also fourteen North American, four South American and four Asian universities. Five institutions (Carnegie Mellon University, Imperial College London, Purdue University, Technical University Denmark, and Norwegian University of Science and Technology) have all more than one hundred publications in CCE. Massachusetts Institute of Technology (MIT) of the USA, the best university of world according to the QS ranking, is in the thirteenth position with eighty five publications. Table 7 presents a list of productive and influential institutions other than universities.

CONICET of Argentina leads Table 7 followed by CNRS of France. CONICET and CNRS have 161 and 148 publications in CCE, respectively. To analyze the performance of institutions in more detail, Table 8 presents temporal evolution of the most productive institutions in CCE.

As expected Carnegie Mellon University from the USA has been the top performing institution in 3 out of 4 analyzed periods (coming second in the fourth period) with Imperial College London from UK performing the best during the years from 1989 to 1998 (and coming the second and the third in the last two decades respectively). CONICET of Argentina has been continuously improving its performance and ranking. The number of publications of CNRS France has been decreasing in the last three decades. During the initial twelve years of CCE, only three universities have more than fifteen publications. In recent years, CCE has been publishing papers from much more diverse geographical world-wide locations. To illustrate a country based performance, Table 9 presents the fifty most productive and influential countries for the journal.

Ranking of the countries has been prepared based on the total publications (TP) indicator. The USA leads by a large margin in all the considered measures of performance. The USA has 2352 publications, 69148 citations, 112 H-index, 29.40 citations per paper, and 129 papers with more than fifty citations. The UK has also performed well and is ranked in the second position in all major categories. The UK has 819 publications, 16677 citations, 61 H-index, 20.36 citations per paper, and 27 papers with more than fifty citations. Six institutions in the UK (Imperial College London, University of Manchester, University College London, University of Leeds, University of Edinburgh and Newcastle University) which are listed in the top 50 institutions, contribute 75% of the total UK publications. Germany, China and Canada are in the third, fourth and fifth position respectively. Note that, only two universities from China (Tsinghua University and Zhejiang University) have made it to the Table 6 of Top 50 institutions and these two universities contributed 105 papers of the 437 papers from China. This result shows that there are several institutions in China which are not in the top 50 but significantly contributed to the country's achieving the fourth position. In the top ten places there are five countries from Europe (UK, Germany, France, Spain, and Italy), two countries from North America (USA and Canada), two countries from South America (Argentina and Brazil) and one country from Asia (China). Twenty three countries have more than one hundred publications in CCE and the top nine have more than two hundred publications. Beside the presentation of citation structure of leading countries, Table 9 also presents publication and citation data relative to the country's population. The indicator 'TP/POP' provides the ratio of the total number of publications per 100 thousand of people while ‘TC/POP’ gives the ratio of the total number of citations per 100 thousand of people. Slovenia leads in the ‘TP/POP’ category followed by Denmark. Slovenia again leads in the ‘TC/POP’ category followed by Norway. Table 10 presents the annual evaluation of leading countries to examine their performance with the progress of time.

Figure 6 presents performance of the top five countries during the last ten years. As expected, the USA has been in the leading position throughout the whole period. The UK and China have been the primary two countries competing for the second position during the last decade. However, China has been significantly improving its performance during the last fifteen years with the last year resulting in 53 published papers taking it to the clear second position. Let us now take a closer look at the most productive and influential super-regions in CCE.

Table 11 confirms the participation of all super-regions in CCE. North America leads in all citation indexes but Europe leads in the total publications index. The top three super-regions, which are North America, Europe and Asia, have more than 1000 publications each. Africa has only ninety seven publications in CCE. Europe and North America received almost 75 per cent of the total number of citations. Finally, let us also more closely examine the citing articles of all CCE publications.

Table 12 depicts the top forty of the authors, universities, countries and journals that have cited the highest number of CCE articles. IE Grossmann is the most contributing author as he referenced CCE articles in 512 of his research publications. Leading authors as listed in Table 5 are also represented in this table. In the list of leading universities, interestingly, CNRS of France comprehensively beats the top two universities (Carnegie Mellon University and Imperial College London) from Table 6. Two Chinese universities, Tsinghua University and Zhejiang University, heavily referenced CCE articles in their research works. They secure the fourth and fifth positions for China. The USA referenced CCE publications in more than 13000 articles. The UK, Germany and France are present in this Table in the third, fourth and fifth position, respectively. The self-citations of CCE (i.e. papers published in CCE citing other CCE papers) are closely followed by the citations from the Industrial Engineering Chemistry Research journal. Five journals have referenced CCE publications in more than 1000 documents (as extracted from WoS database). According to Table 12, six journals (Industrial Engineering Chemistry Research, Computer Aided Chemical Engineering, Chemical Engineering Science, AIChE Journal, Journal of Process Control, and Chemical Engineering Research Design) are closely connected with CCE. To obtain more detailed insights of the results, the following section presents graphical visualizations of bibliographic coupling, co-authorship, co-citation and co-occurrence of keywords.

4. Mapping CCE related information with VOS viewer software

This section presents graphical visualizations of co-citation of journals and authors, co-occurrence of keywords, and bibliographic coupling of institutions using the VOS viewer software. The VOS viewer software forms network visualization based on weight and link strength. The size of a node depends on its weight. The link strength of a node determines its connective edges with other nodes. Let us first concentrate on the co-citation of journals with CCE. Co-citation of journals occurs when two documents of two different journals receive a citation from a same third document (Small, 1973). Figure 7 presents the co-citation of journals in CCE. Please note that, to construct this figure we have set the minimum co-citation threshold to 80 and link strength to 100. This means that we exclude those journals whose co-citations with CCE are less than 80 and/or link strength is less than 100.

Industrial Engineering Chemistry Research has 10708 co-citations and 8678.05 link strength, which results in the best co-citation union with CCE. AIChE Journal and Chemical Engineering Science are the other two journals, the significant presence of which can be easily seen in Figure 7. AIChE Journal and Chemical Engineering Science have 10110 and 8003 co-citations with CCE, respectively. Journal of Process Control, Automatica, and Chemical Engineering Research Design are also highlighted in Figure 7 as they have more than 1500 co-citations and 1400-link strength with CCE. For the temporal analysis of co-citation of journals with CCE, Figures 8, 9, 10 and 11 depict co-citation of journals in CCE for the intervals of 1977-1988, 1989-1998, 1999-2008 and 2009-2018, respectively.

Self-citation within CCE is the most prominent in Figures 9, 10 and 11. AIChE Journal had the best co- citations and co-citation link strength with CCE during 1977 to 1988 period. Excluding the self-citation, Industrial Engineering Chemistry Research leads in the intervals 2009-2018 and 1999-2008 while Aiche Journal leads in the interval 1989-1998. Figures 8 to 11 ascertain that AIChE Journal, Chemical Engineering Science, Industrial Engineering Chemistry Research and CCE have had a very close bond over the years. Table 13 presents all the relevant data regarding co-citation and co-citation link strength of journals collaborations with CCE.

Figure 12 presents a network visualization of co-citation of authors in CCE. There are three major clusters (Green, Red and Blue) in Figure 12. Christodoulos A. Floudas, B Linnhoff , JM Douglas are the most important/dominant nodes in the green cluster. Lorenz T. Biegler, Rafiqul Gani, Wolfgang Marquardt, and Constantinos Pantelides play a vital role in the formation of red cluster. WL Luyben leads the blue cluster along with Gregory Stephanopoulos.

Let us now take a closer look at the Figures 13 and 14 for bibliographic coupling of institutions and countries publishing in CCE. Bibliographic coupling occurs when two different studies cite a common reference of a third work in their bibliographies (Kessler, 1963).

To construct Figure 13 we restricted the minimum publication threshold to 10 documents and minimum link strength to 100 links. Carnegie Mellon University, Imperial College London, Purdue University, and Texas A&M U College Station are showing their big presence in Figure 13. National University of Singapore, Princeton University, University of Illinois, Indian Institute of Technology, and University of Wisconsin are also playing an important role for research collaboration in CCE. Specifically, we can say that the leading institutions from Table 6 are also playing the same role for research collaboration in CCE.

Figure 14 presents bibliographic coupling of countries publishing in CCE. Note that, we exclude those countries from Figure 14 whose number of publications in CCE is less than five documents. Moreover, we do not display those edges whose link strength is less than 50 links. USA, UK, Germany, Canada and China are showing their high influence in Figure 14. Thus, most productive and influential countries listed in Table 9 are also appearing in Figure 14. The difference is that Figure 14 shows how the leading countries connect between each other while Table 9 presents a ranking according to the number of publications and citations. Note that from a general point of view, countries from a same region tend to connect more so they usually appear close to each other in the figures of bibliographic coupling. Finally, we construct graphical visualization of co-occurrence of keywords listed in CCE publications. Keywords provided by authors together with their publication help to categorize and outline the publication more easily and quickly. The keywords co-occurrence exploration helps to depict the most often discussed topics in the journal and their relation with others topics. Figure 15 presents co-occurrence of keywords used by the authors in their publications in CCE from 1977 to 2018. Moreover, to depict the trends of topics with the progress of time, Figures 16, 17, and 18 visualize the network of topics co-occurrence for the periods of 1989-1998, 1999 -2008 and 2009-2018, respectively.

Figure 15 shows that Optimization, Simulation, Scheduling, Model Predictive Control, Process Synthesis, Process Control, Uncertainty and Modelling have been the most commonly used keywords by the authors in their publications in CCE. Recall that, 17 articles out of the top 50 most cited articles of CCE use optimization as the key subject. Optimization, Dynamic Simulation, Process Synthesis and Simulation are the top four keywords used by the authors during 1989 to 1998. Optimization, Simulation, Scheduling, Process Control, Genetic Algorithm, and Model Predictive Control are the most often discussed topics during 1999 to 2008. In the last decade (i.e. from 2009 to 2018), the keywords of Optimization, Simulation, Model Predictive Control, Scheduling, Uncertainty, Multi-Objective Optimization, and Global Optimization are discussed by the authors in more than 50 of the CCE publications. Optimization and Simulation are the heavily used keywords in the CCE publications throughout the time. Table 14 provides a more detailed data of the most often used keywords in the CCE publications.

5. Conclusions

CCE began its journey in 1977 and has already completed its forty eventful years. During this amazing journey, it has published a number of excellent research findings and established its high reputation in the field of chemical engineering. In 2017, this SCI indexed journal had an impact factor of 3.113. This bibliomeric retrospective study has analyzed CCE publications in celebration of its four very successful decades. The study has collected data from the WoS and summarized them using several well established performance measures. It has considered all publications in CCE from 1977 to the end of 2018 and explored the foremost developments in terms of impact, authors, universities, countries and subjects of research.

This study has revealed numerous interesting aspects about CCE publications and some of the main findings are as follows. The journal had the best publication rate during the 1996 to 2000 period. It published the largest number of articles in 1996. Publications from 1997 to 2006 period not only received the highest number of citations but also had the highest citation rate. The year 2004 was the year of publications receiving highest citations for CCE. Thirty CCE publications have crossed the threshold of 250 citations and thirteen among them have more than 400 citations. The research paper published in the year 1993 and written by J. J. Downs & E. F Vogel entitled “A Plant-Wide Industrial-Process Control Problem” has received the highest number of citations. Review and state-of-art based studies are likely to receive more citations and as a result these types of works are heavily present in the list of the top 50 most often cited CCE papers. One third of these top 50 papers discussed optimization related issues. Professor Ignacio E. Grossmann of Carnegie Mellon University has been the most influential author of the journal as he leads in all major categories with 206 publications, 12380 citations and H-index of 62. Carnegie Mellon University of the USA has been the most productive university in CCE followed by the Imperial College London of the UK. The USA leads in all the major categories followed by the UK and Germany. Temporal analysis has shown the USA as the leading country throughout the years with China quickly emerging during last five years as the main competitor for the upcoming period. Among the all supranational regions, North America leads in all the performance indexes with the exception of the total number of publications in CCE where Europe tops the ranking. Co-citation analysis of journals has revealed that Industrial Engineering Chemistry Research, AIChE Journal, and Chemical Engineering Science are very closely bonded with CCE. The most productive authors, institutions, and countries have also dominated the bibliographic coupling analysis in CCE. Co-occurrence of authors' keywords has revealed that Optimization, Simulation, Scheduling, Model Predictive Control, Process Synthesis, Process Control, Uncertainty and Modelling are the most often used keywords by the authors in their CCE publications.

This bibliometric study has analyzed the publication and citation patterns of CCE using different performance related indexes. Beside celebrating and analyzing the contribution of the authors, institutions and countries, it has explored the most often covered and discussed topics in the CCE publications. It is hoped that the contribution of the present study will help young researchers and academics to appreciate the history of the field, identify potential research gaps and more easily find the relevant topics most suitable for the future dissemination and publication in CCE. This work has relied on the established and most often used publication related performance indexes with all their known strong and weak points. As such, any future analyses and rankings are likely to use an improved methodology in this very dynamically changing area of bibliometric analyses.

Conflict of Interest:

There is no conflict of interest with the subject matter or research presented in the manuscript.

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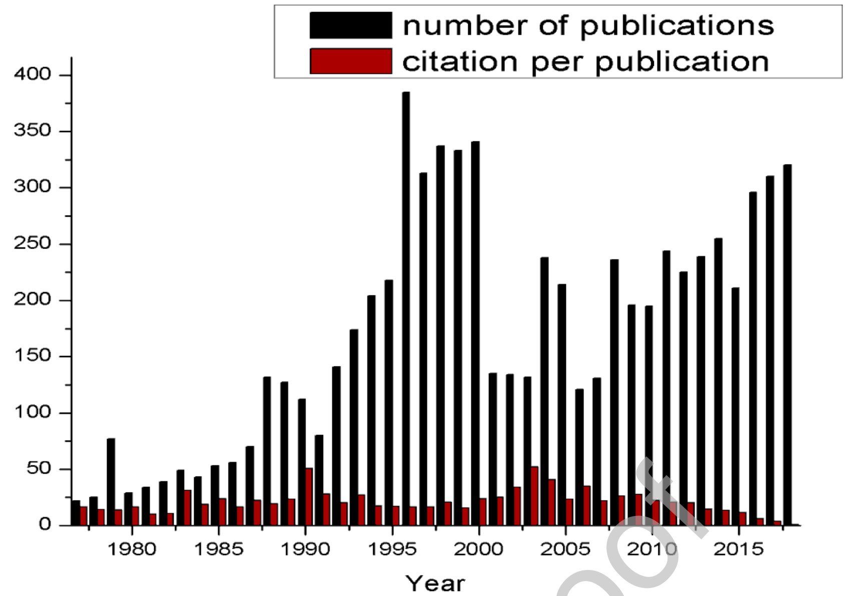

Figure 1. Annual number of publications vs citation per publication published in CCE

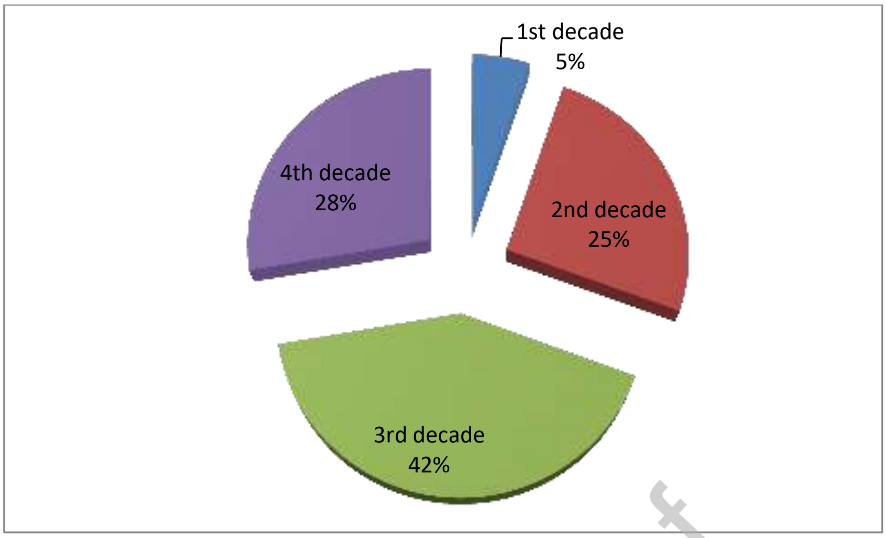

Figure 2. Citation distribution of CCE publications over the four decades

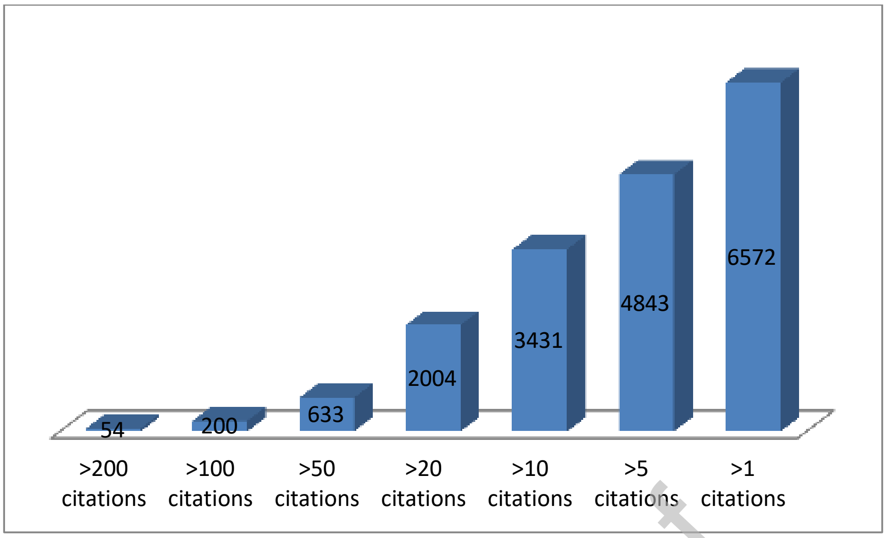

Figure 3. Number of publications above the seven citation thresholds

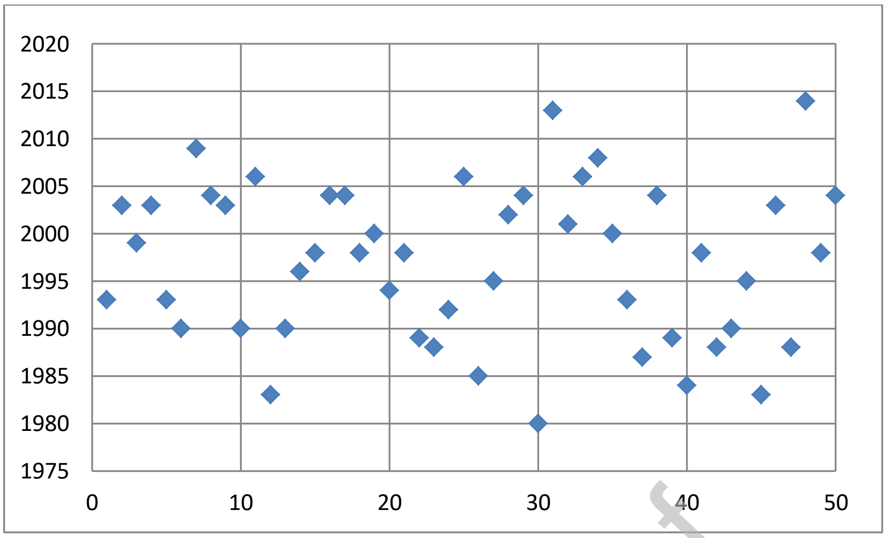

Figure 4. Temporal visualization of the 50 most cited documents in CCE

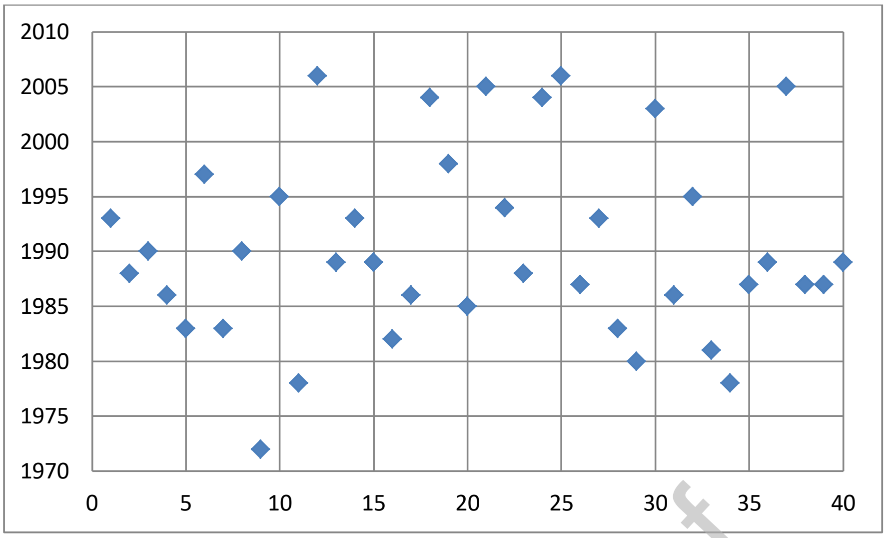

Figure 5. Time-based visualization of the most cited documents in CCE

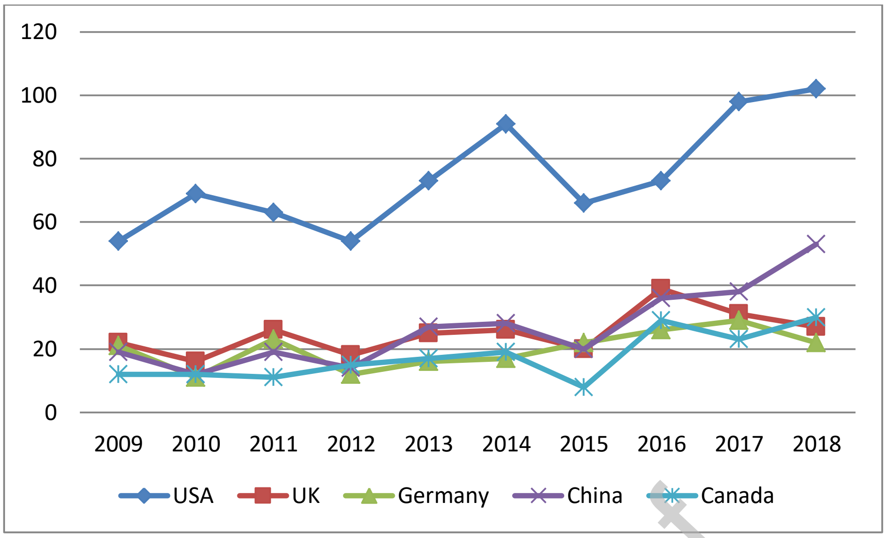

Figure 6. Annual performance of top five countries in the last ten years

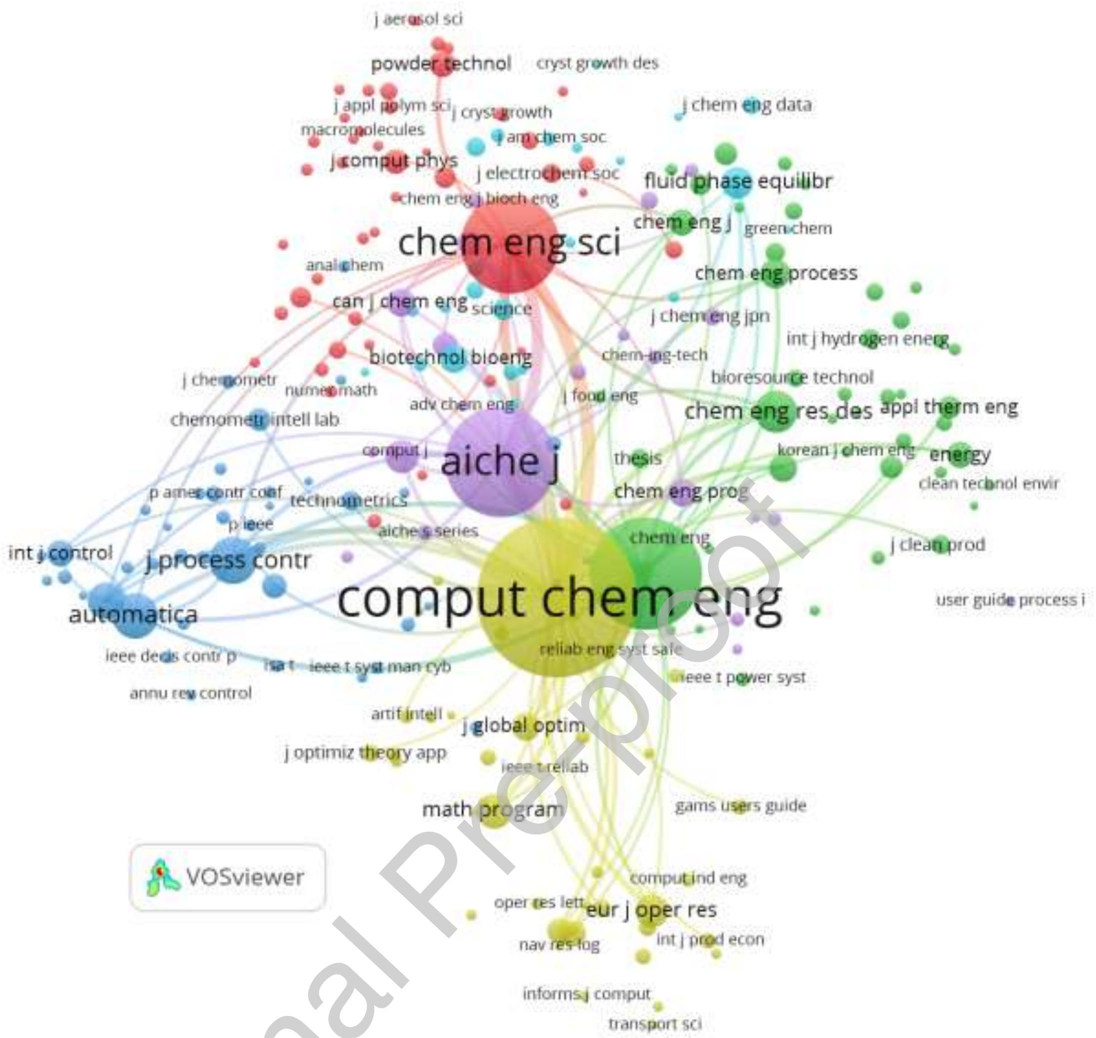

Figure 7. Co-citation of journals in CCE: minimum citation threshold of 80 and 100 links

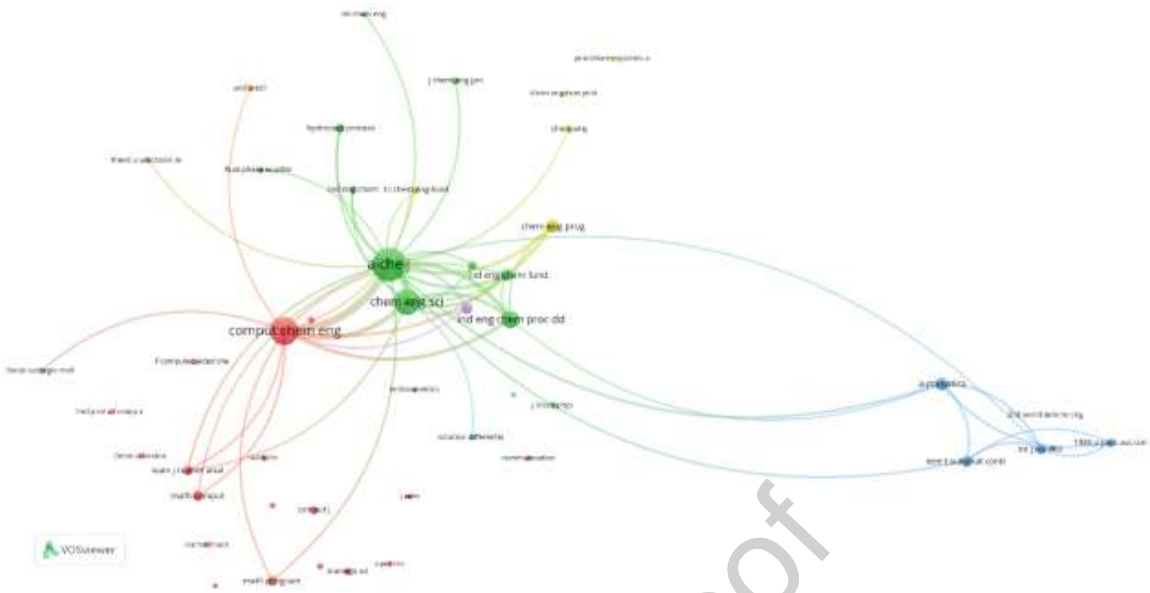

Figure 8. Co-citation of journals in CCE: 1977-1988 (minimum citation threshold of 20 and 50 links)

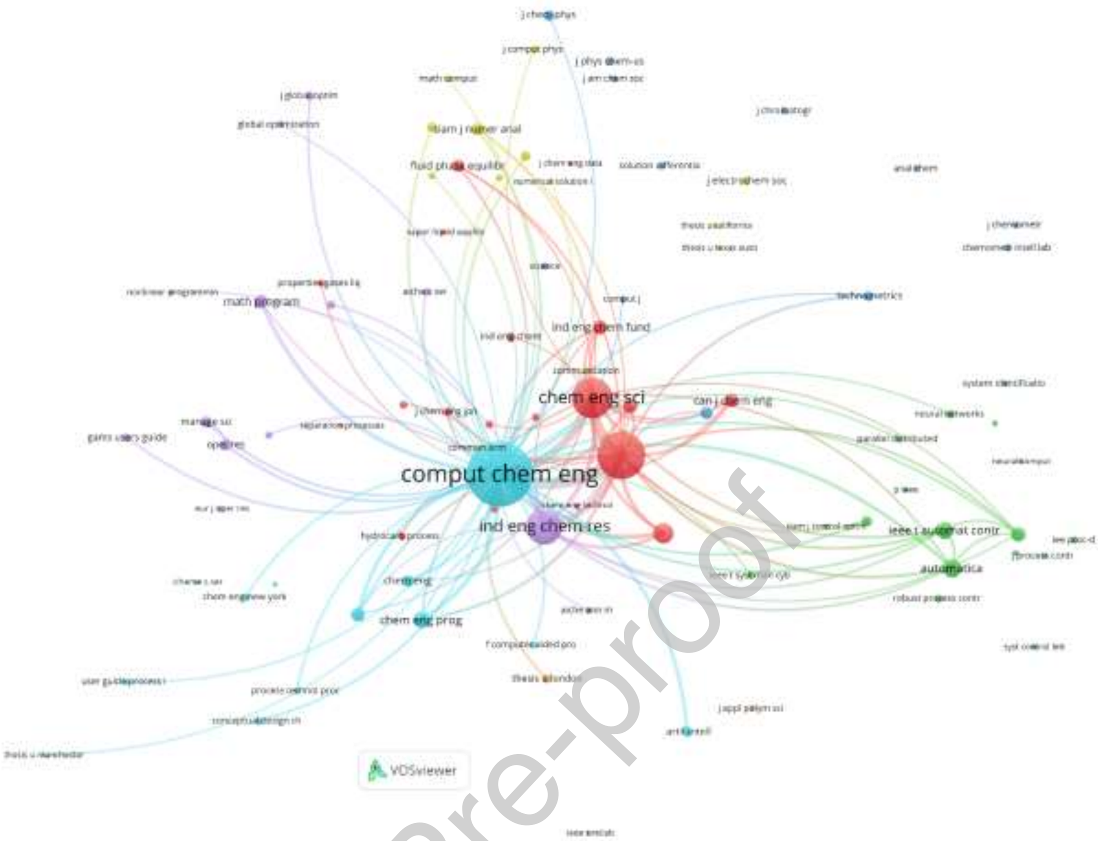

Figure 9. Co-citation of journals in CCE: 1989-1998 (minimum citation threshold of 30 and 100 links)

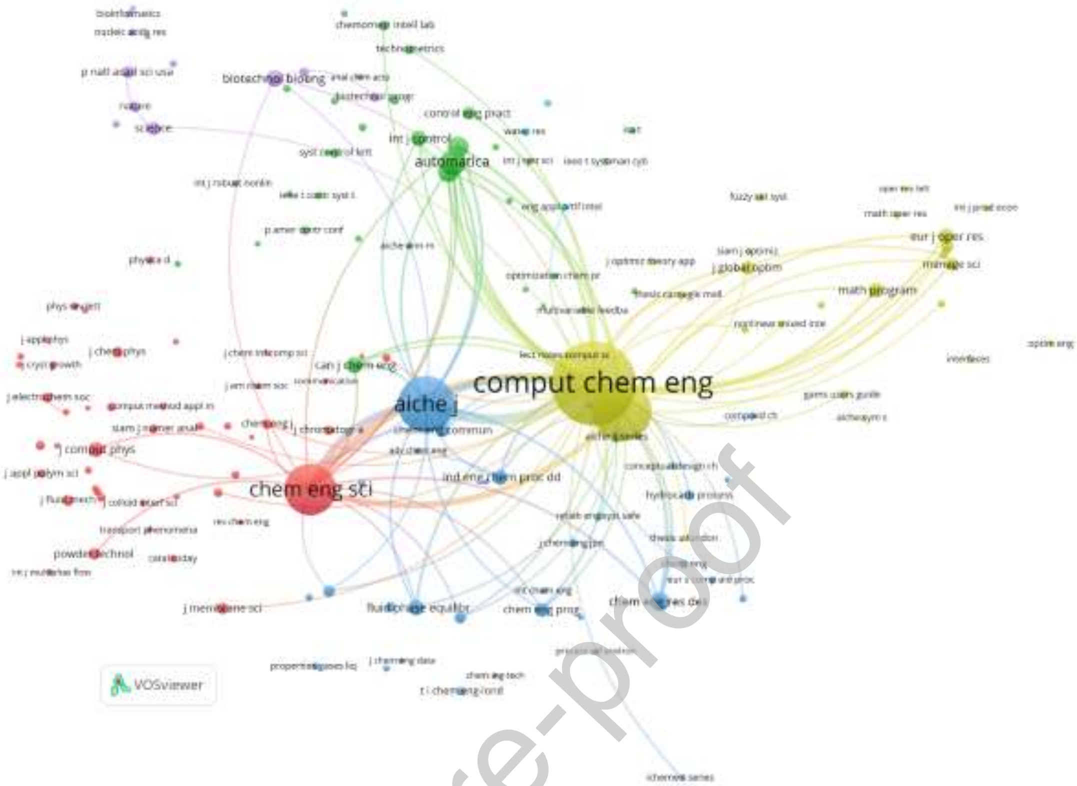

Figure 10. Co-citation of journals in CCE: 1999-2008 (minimum citation threshold of 40 and 100 links)

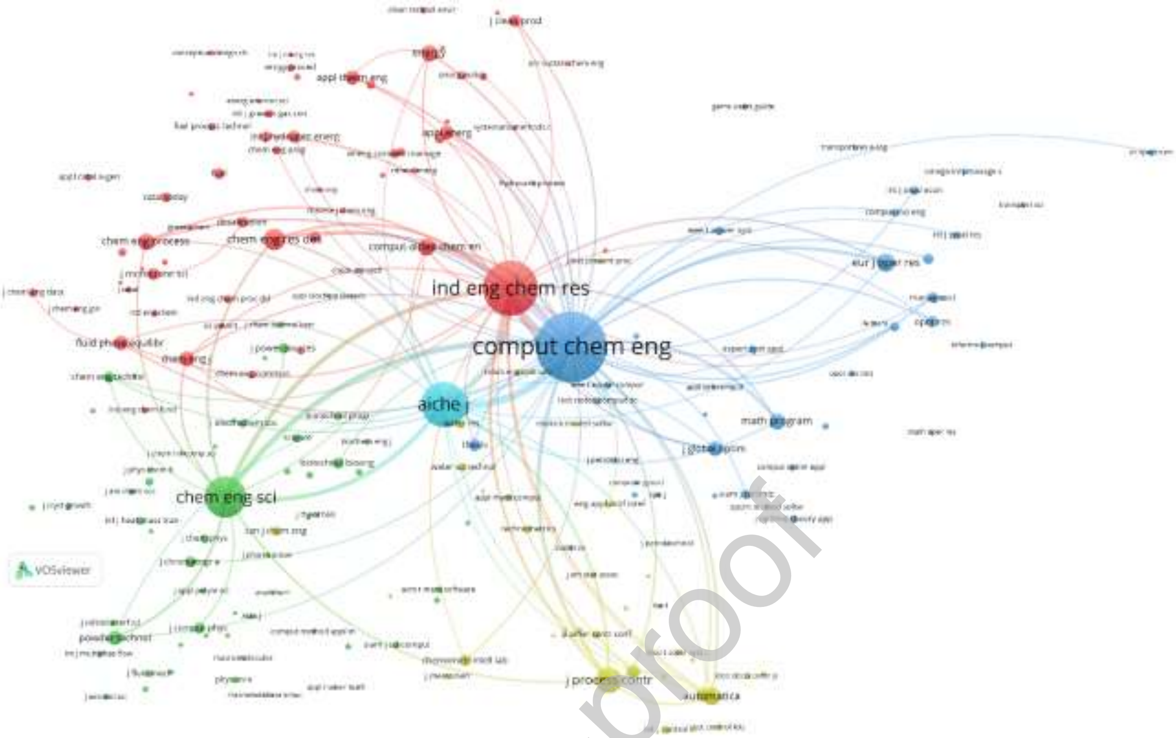

Figure 11. Co-citation of journals in CCE: 2009-2018 (minimum citation threshold of 50 and 100 links)

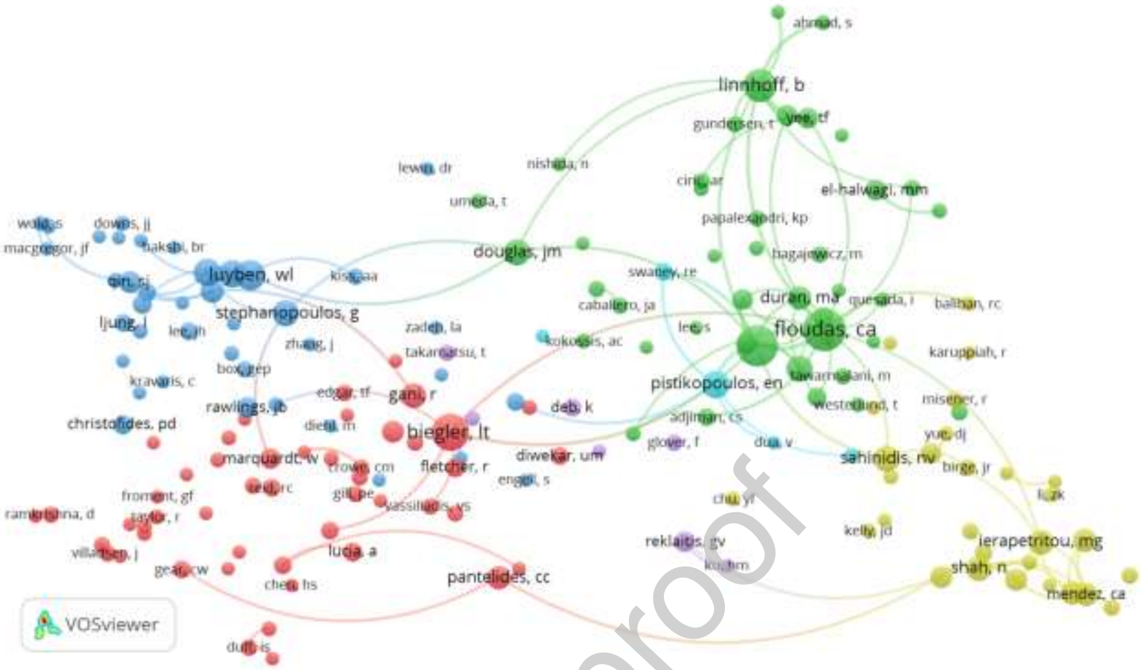

Figure 12. Co-citation of authors in CCE: minimum citation threshold of 5 and 100 links

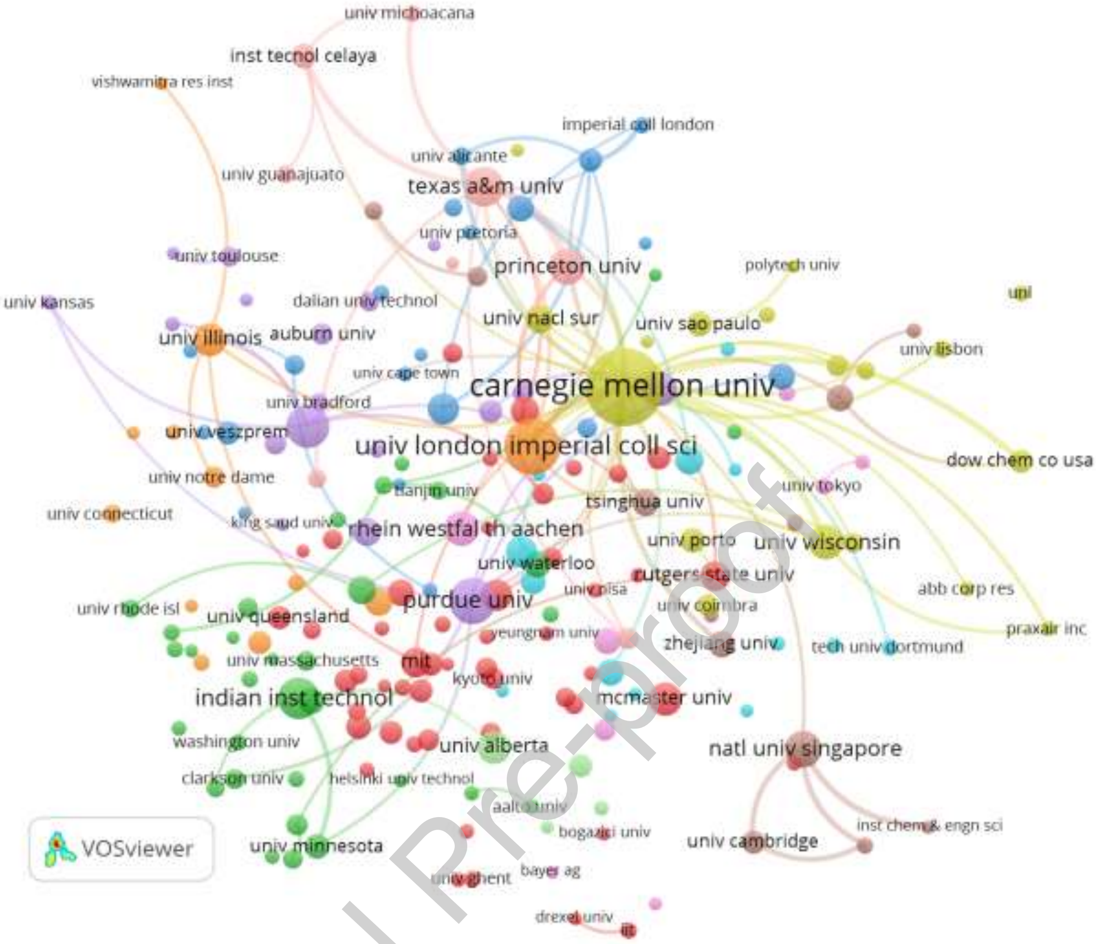

Figure 13. Bibliographic coupling of institutions publishing in CCE: minimum publication threshold of 10 documents and 100 links

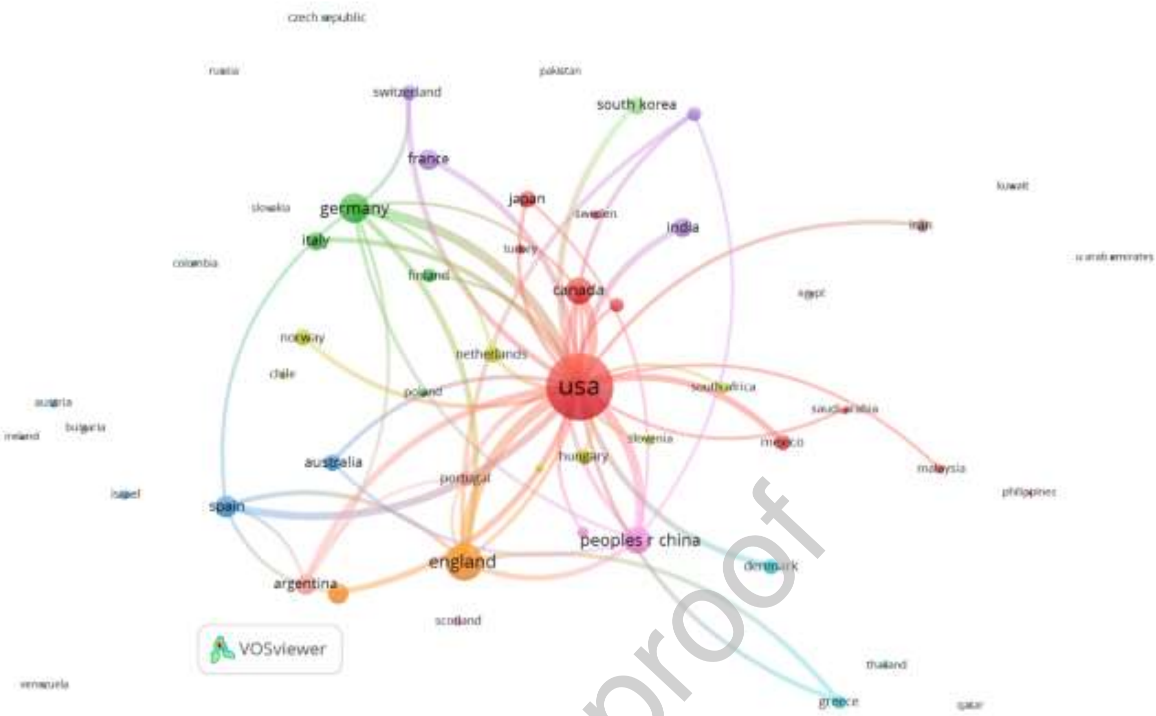

Figure 14. Bibliographic coupling of countries publishing in CCE: minimum publication threshold of 5 documents and 50 links

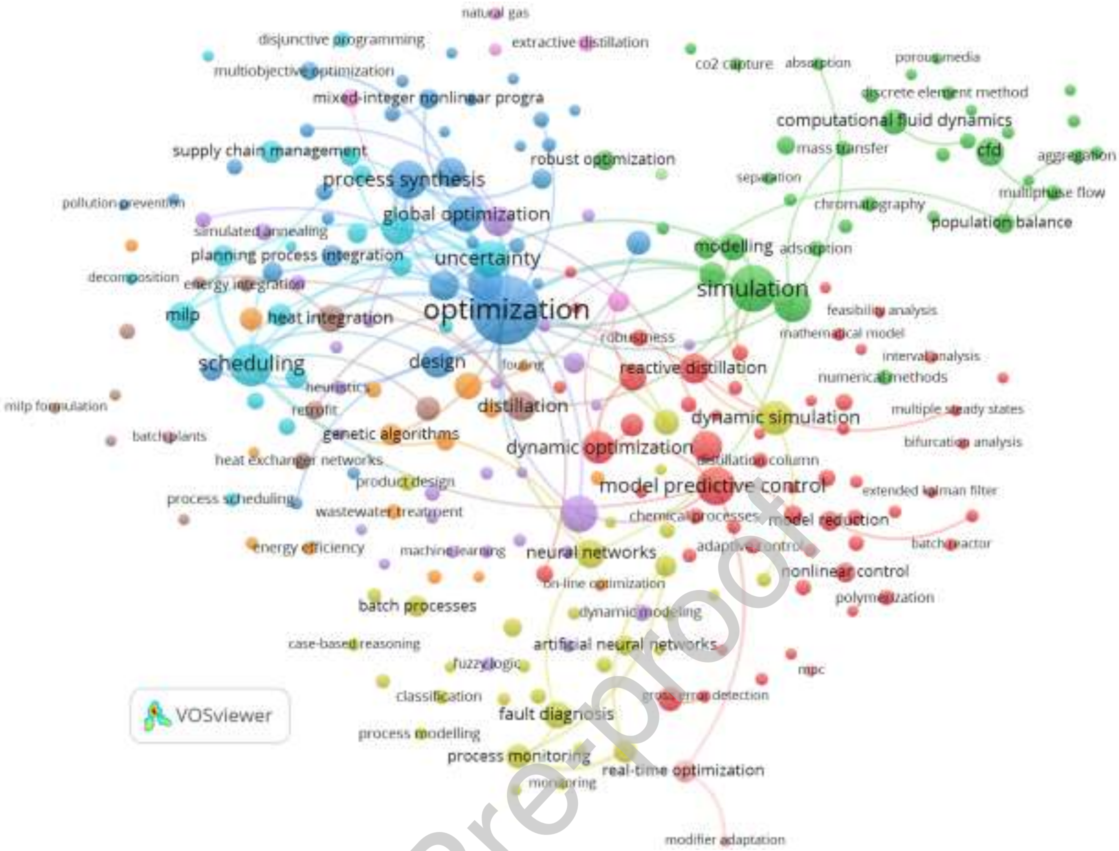

Figure 15. Co-occurrence of author keywords in CCE: minimum occurrence threshold of 80 and 100 links

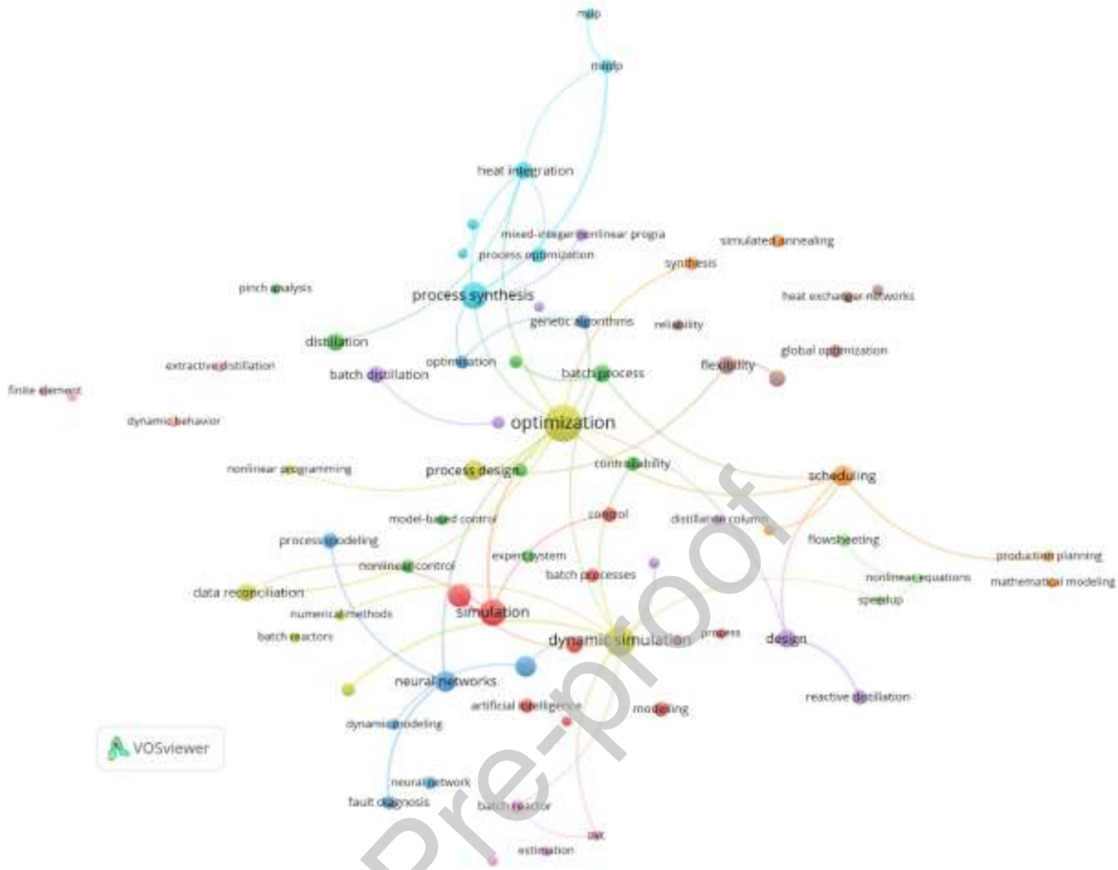

Figure 16. Co-occurrence of author keywords in CCE: 1989-1998 (minimum occurrence threshold of 5 and 50 links)

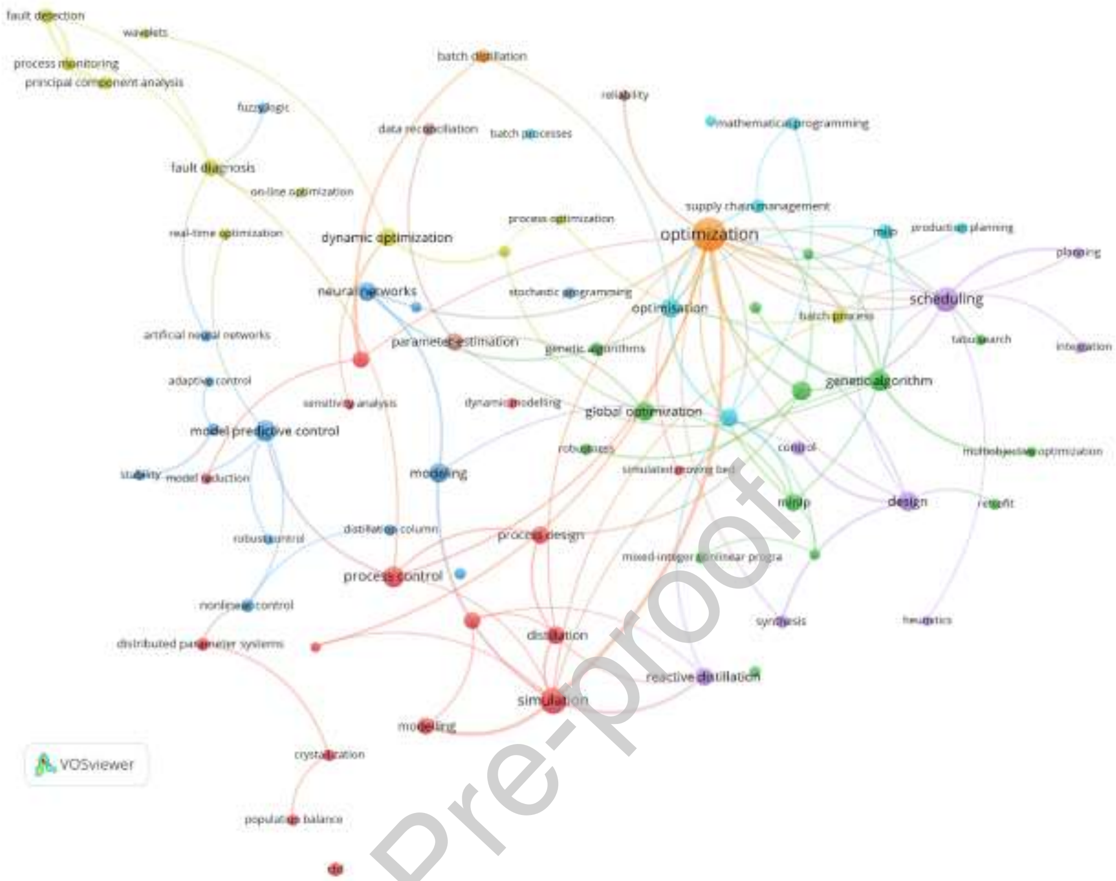

Figure 17. Co-occurrence of author keywords in CCE: 1999-2008 (minimum occurrence threshold of 10 and 100 links)

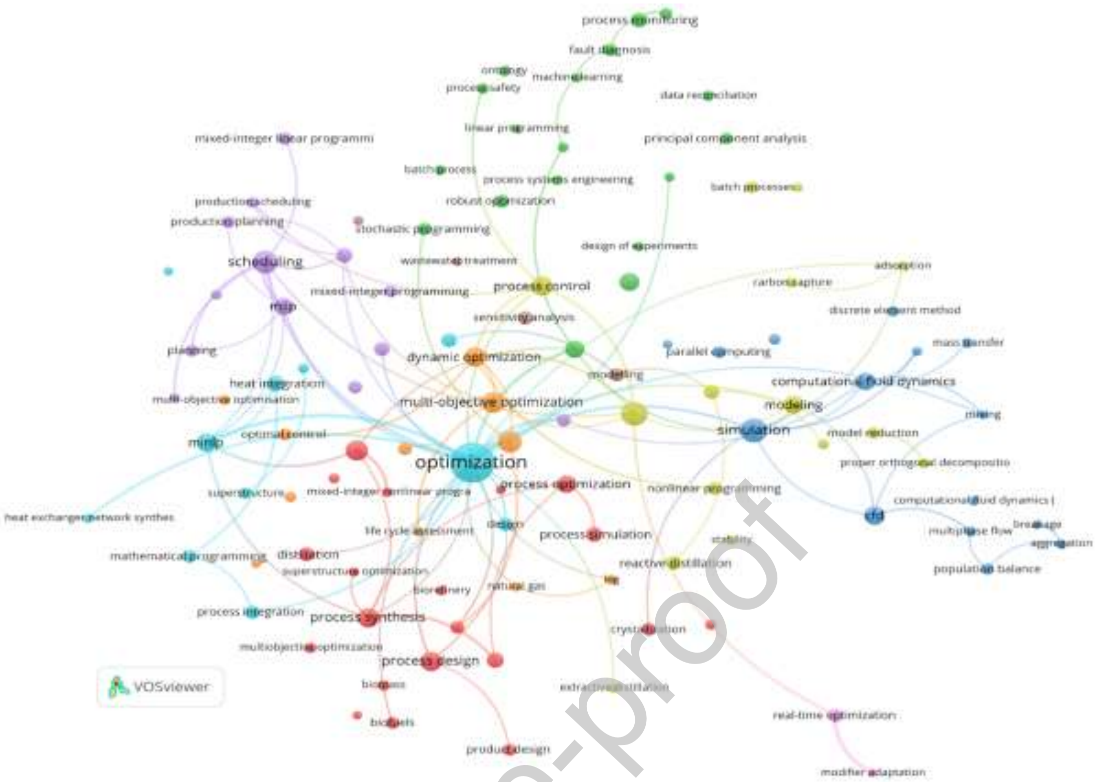

Figure 18. Co-occurrence of author keywords in CCE: 2009-2018 (minimum occurrence threshold of 10 and 100 links)

Table 1. List of bibliometric studies to celebrate anniversary of academic/scientific journals

Publisher	Bibliometric Study	Anniversary	Name of the Journal
Elsevier	Merigó et al., (2015)	40 year	Journal of Business Research
	Merigó et al., (2018b)	50 year	Information Sciences
	Cancino et al., (2017)	40 years	Computers & Industrial Engineering
	Laengle et al., (2017)	40 years	European Journal of Operational Research
	Merigó,et al. (2019b)	40 years	Safety Science
	Merino et al., (2006)	25 years	Technovation
	Cobo et al., (2015)	25 years	Knowledge-Based Systems
	Modak et al., (2019)	50 years	Transportation Research Part A: Policy and Practice
Springer	Mas-Tur et al., (2018)	50 Years	Quality & Quantity
	Laengle et al., (2018c)	25 years	Group Decision and Negotiation
Wiley	Merigó et al., (2017)	30 years	International Journal of Intelligent Systems
	Ramos-Rodríguez and Ruíz-Navarro (2004)	20 years	Strategic Management Journal
	Biemans et al., (2007)	20 years	Journal of Product Innovation Management
Emerald	Martínez-López et al., (2018)	50 years	European Journal of Marketing
	Valenzuela et al., (2017)	30 years	Journal of Business & Industrial

			Marketing
	Gaviria-Marin (2018)	20 years	Journal of Knowledge Management
Taylor & Francis	Laengle et al., (2018b)	30 years	International Journal of Computer Integrated Manufacturing
World Scientific	Wang et al., (2018)	25 years	International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems

Table 2. Annual citation structure of CCE

Year	TP	TC	>200	>100	>50	>20	>10	>5	>1
1977	22	365	0	0	3	6	11	14	19
1978	25	356	0	0	2	5	8	13	24
1979	77	1,050	1	3	5	13	26	30	55
1980	29	474	1	1	1	3	8	15	25
1981	34	345	0	0	1	5	10	14	30
1982	39	418	0	1	1	4	7	20	33
1983	49	1,526	2	3	7	13	23	35	48
1984	43	808	1	2	2	11	24	27	37
1985	53	1,267	1	3	7	18	28	37	47
1986	56	913	0	0	4	18	28	36	51
1987	70	1,562	1	2	8	24	34	50	65
1988	132	2,537	3	3	10	34	58	83	120
1989	127	2,952	2	8	16	35	61	86	118
1990	112	5,683	4	14	34	61	82	93	107
1991	80	2,238	0	6	13	32	52	61	76
1992	141	2,851	1	6	14	35	56	75	121
1993	174	4,747	3	8	18	42	61	90	151
1994	204	3,566	2	6	18	51	76	108	183
1995	218	3,711	3	7	15	45	80	136	204
1996	385	6,309	1	7	24	91	158	257	355
1997	313	5,236	0	4	25	85	147	223	295
1998	337	6,925	5	10	28	97	160	246	327
1999	333	5,237	2	12	23	56	87	130	260
2000	341	8,152	2	9	37	128	212	269	330
2001	135	3,430	0	4	18	57	100	122	133
2002	134	4,576	1	11	30	66	97	119	132
2003	132	6,902	5	9	29	67	98	120	128
2004	238	9,704	6	19	54	124	187	218	235
2005	214	4,999	0	4	22	91	150	190	208
2006	121	4,236	3	7	19	55	84	105	117
2007	131	2,866	0	3	15	53	80	106	128
2008	236	6,186	1	6	30	110	174	211	232
2009	196	5,361	1	9	22	81	131	171	194
2010	195	4,377	0	3	18	76	137	175	194
2011	244	5,001	0	3	20	85	154	200	235
2012	225	4,584	0	3	22	83	139	183	219

2013	239	3,525	1	2	9	50	124	179	230
2014	255	3,404	1	2	7	46	121	184	247
2015	211	2,430	0	0	2	33	80	158	207
2016	296	1,839	0	0	0	13	59	155	274
2017	310	1,110	0	0	0	2	17	89	258
2018	320	253	0	0	0	0	2	10	120
Total	7226	144011	54	200	633	2004	3431	4843	6572
%	100%		0.75%	2.77%	8.76%	27.73%	47.48%	67.02%	90.95%

Abbreviations: TP and TC = Total papers and citations; >200, >100, >50, >20, >10, >5, >1 = Number of papers with more than 200, 100, 50, 25, 10, 5 and 1 citations.

Table 3. The 50 most cited documents in CCE

R	TC	TC (Scopus)	Title	Author/s	Year	C/Y	C/Y (Scopus)
1	1174	**1745**	A Plant-Wide Industrial-Process Control Problem	Downs, JJ; Vogel, EF	1993	48.92	67.12
2	1145	**1762**	A Review Of Process Fault Detection And Diagnosis Part I: Quantitative Model-Based Methods	Venkatsubramanian, V; Rengaswamy, R; Yin, K; et al.	2003	81.79	110.13
3	989	**1384**	Model Predictive Control: Past, Present And Future	Morari, M; Lee, JH	1999	54.94	69.20
4	813	**1229**	A Review Of Process Fault Detection And Diagnosis Part Iii: Process History Based Methods	Venkatasubramanian, V; Rengaswamy, R; Kavuri, SN; et al.	2003	58.07	76.81
5	679	**862**	A General Algorithm For Short-Term Scheduling Of Batch-Operations .1. Milp Formulation	Kondili, E; Pantelides, Cc; Sargent, RWH	1993	28.29	33.15
6	583	**831**	Simultaneous-Optimization Models For Heat Integration .2. Heat-Exchanger Network Synthesis	Yee, TF; Grossmann, IE; Kravanja, Z	1990	21.59	28.66
7	575	**892**	Data-Driven Soft Sensors In The Process Industry	Kadlec, P; Gabrys, B; Strandt, S	2009	71.88	89.20
8	559	**767**	Optimization Under Uncertainty: State-Of-The-Art And Opportunities	Sahinidis, NV	2004	43.00	51.13
9	537	**812**	A Review Of Process Fault Detection And Diagnosis Part Ii: Quantitative Model And Search Strategies	Venkatasubramanian, V; Rengaswamy, R; Kavuri, SN	2003	38.36	50.75
10	479	**561**	A Combined Penalty-Function And Outer-Approximation Method For Minlp Optimization	Viswanathan, J; Grossmann, IE	1990	17.74	19.34
11	456	**609**	State-Of-The-Art Review Of Optimization Methods For Short-Term Scheduling Of Batch Processes	Mendez, CA; Cerda, J; Grossmann, IE; et al.	2006	41.45	46.85
12	447	**583**	A Structural Optimization Approach In Process Synthesis .2. Heat-Recovery Networks	Papoulias, SA; Grossmann, IE	1983	13.15	16.19
13	429	**528**	Use Of Neural Nets For Dynamic Modeling And Control Of Chemical Process Systems	Bhat, N; Mcavoy, TJ	1990	15.89	18.21
14	369	**493**	Nonlinear Principal Component Analysis - Based On Principal Curves And Neural Networks	Dong, D; Mcavoy, TJ	1996	17.57	21.43
15	364	**494**	Recursive Pls Algorithms For Adaptive Data Modeling	Qin, SJ	1998	19.16	23.52
16	363	**469**	Continuous-Time Versus Discrete-Time Approaches For Scheduling Of Chemical Processes: A Review	Floudas, CA; Lin, XX	2004	27.92	31.27
17	329	**415**	Retrospective On Optimization	Biegler, LT; Grossmann, IE	2004	25.31	27.67
18	311	**413**	Nonlinear Model Predictive Control: Current Status And Future Directions	Henson, MA	1998	16.37	19.67
19	309	**385**	A Review Of Recent Design Procedures For Water Networks In Refineries And Process Plants	Bagajewicz, M	2000	18.18	20.26
20	302	**381**	Modeling And Computational Techniques For Logic-Based Integer Programming	Raman, R; Grossmann, IE	1994	13.13	15.24
21	293	**368**	A Global Optimization Method, Alpha Bb, For General Twice-Differentiable Constrained Nlps - I. Theoretical Advances	Adjiman, CS; Dallwig, S; Floudas, CA; et al.	1998	15.42	17.52
22	292	**374**	New Insights In Solving Distributed System Equations By The Quadrature Method .1. Analysis	Quan, JR; Chang, CT	1989	10.43	12.47
23	291	**343**	Generic Model Control (Gmc)	Lee, PL; Sullivan, GR	1988	10.03	11.06
24	288	**371**	Nonlinear Pls Modeling Using Neural Networks	Qin, SJ; Mcavoy, TJ	1992	11.52	13.74
25	286	**335**	Global Optimization For The Synthesis Of Integrated Water Systems In Chemical Processes	Karuppiah, R; Grossmann, IE	2006	26.00	25.77
26	283	**327**	Sensitivity Analysis Of Initial-Value Problems With Mixed Odes And Algebraic Equations	Caracotsios, M; Stewart, WE	1985	8.84	9.62

27	276	**368**	Plant-Wide Control Of The Tennessee Eastman Problem	Lyman, PR; Georgakis, C	1995	12.55	15.33
28	274	**476**	A Modular Simulation Package For Fed-Batch Fermentation: Penicillin Production	Birol, G; Undey, C; Cinar, A	2002	18.27	28.00
29	273	**385**	Fault Diagnosis Based On Fisher Discriminant Analysis And Support Vector Machines	Chiang, LH; Kotanchek, ME; Kordon, AK	2004	21.00	25.67
30	264	**328**	Optimal Water Allocation In A Petroleum Refinery	Takama, N; Kuriyama, T; Shiroko, K; et al.	1980	7.14	8.41
31	248	**428**	Distributed Model Predictive Control: A Tutorial Review And Future Research Directions	Christofides, PD; Scattolini, R; Munoz De La Pena, D; et al.	2013	62.00	71.33
32	247	**362**	Managing Demand Uncertainty In Supply Chain Planning	Gupta, A; Maranas, CD	2001	15.44	20.11
33	246	**367**	An Overview Of Subspace Identification	Qin, SJ	2006	22.36	28.23
34	239	**340**	Data-Based Process Monitoring, Process Control, And Quality Improvement: Recent Developments And Applications In Steel Industry	Kano, M; Nakagawa, Y	2008	26.56	30.91
35	233	**298**	Planning And Scheduling Models For Refinery Operations	Pinto, JM; Joly, M; Moro, LFL	2000	13.71	15.68
36	233	**278**	A General Algorithm For Short-Term Scheduling Of Batch-Operations .2. Computational Issues	Shah, N; Pantelides, CC; Sargent, RWH	1993	9.71	10.69
37	232	**292**	Active Constraint Strategy For Flexibility Analysis In Chemical Processes	Grossmann, IE; Floudas, CA	1987	7.73	9.13
38	229	**315**	Control Structure Design For Complete Chemical Plants	Skogestad, S	2004	17.62	21.00
39	229	**265**	Simultaneous-Optimization And Solution Methods For Batch Reactor Control Profiles	Cuthrell, JE; Biegler, LT	1989	8.18	8.83
40	229	**272**	Solution Of Dynamic Optimization Problems By Successive Quadratic-Programming And Orthogonal Collocation	Biegler, LT	1984	6.94	7.77
41	226	**299**	Control Performance Monitoring - A Review And Assessment	Qin, SJ	1998	11.89	14.24
42	226	**279**	Artificial Neural Network Models Of Knowledge Representation In Chemical-Engineering	Hoskins, JC; Himmelblau, DM	1988	7.79	9.00
43	225	**299**	Simultaneous-Optimization Models For Heat Integration .1. Area And Energy Targeting And Modeling Of Multi-Stream Exchangers	Yee, TF; Grossmann, IE; Kravanja, Z	1990	8.33	10.31
44	223	**270**	Global Optimization Of Nonconvex Nlps And Minlps With Applications In-Process Design	Ryoo, HS; Sahinidis, NV	1995	10.14	11.25
45	222	**296**	A Structural Optimization Approach In Process Synthesis .1. Utility Systems	Papoulias, SA; Grossmann, IE	1983	6.53	8.22
46	220	**318**	Dynamic Optimization Of Batch Processes - I. Characterization Of The Nominal Solution	Srinivasan, B; Palanki, S; Bonvin, D	2003	15.71	19.88
47	216	**264**	The Synthesis Of Cost Optimal Heat-Exchanger Networks - An Industrial Review Of The State Of The Art	Gundersen, T; Naess, L	1988	7.45	8.52
48	213	**364**	Biomass-To-Bioenergy And Biofuel Supply Chain Optimization: Overview, Key Issues And Challenges	Yue, D; You, F; Snyder, SW	2014	71.00	72.80
49	212	**368**	A Global Optimization Method, Alpha Bb, For General Twice-Differentiable Constrained Nlps - Ii. Implementation And Computational Results	Adjiman, CS; Androulakis, IP; Floudas, CA	1998	11.16	17.52
50	211	**288**	Multi-Objective Optimization Of Multi-Echelon Supply Chain Networks With Uncertain Product Demands And Prices	Chen, CL; Lee, WC	2004	16.23	19.20

Abbreviations: R = Rank; TC = Total citations; C/Y = Citations per year.

Table 4. Top 40 most cited documents in CCE publications

Rank	Year	First Author	Reference	Vol	Page	Type	TC	Co-citations
1	1993	Kondili E	Comput Chem Eng	v17	p211	A	177	144
2	1988	Douglas JM	Conceptual Design Ch			B	156	91
3	1990	Viswanathan J	Comput Chem Eng	v14	p769	A	134	121
4	1986	Duran MA	Math Program	v36	p307	A	132	124
5	1983	Papoulias SA	Comput Chem Eng	v7	p707	A	110	100
6	1997	Biegler LT	Systematic Methods C			B	106	83
7	1983	Linnhoff B	Chem Eng Sci	v38	p745	A	106	95
8	1990	Yee TF	Comput Chem Eng	v14	p1165	A	100	93
9	1972	Geoffrion AM	Journal Of Optimization Theory And Applications	v10	p237	A	99	94
10	1995	Floudas CA	Nonlinear Mixed Inte			B	97	90
11	1978	Villadsen J	Solution Differentia			B	96	43
12	2006	Mendez CA	Comput Chem Eng	v30	p913	A	93	88
13	1989	Morari M	Robust Process Contr			B	90	49
14	1993	Downs JJ	Comput Chem Eng	v17	p245	A	89	41
15	1989	Goldberg DE	Genetic Algorithms S			B	87	43
16	1982	Linnhoff B	User Guide Process I			B	86	65
17	1986	Floudas CA	AIChE J	v32	p276	A	84	79
18	2004	Floudas CA	Comput Chem Eng	v28	p2109	A	83	81
19	1998	Ierapetritou MG	Ind Eng Chem Res	v37	p4341	A	80	79
20	1985	Swaney RE	AIChE J	v31	p621	A	80	65
21	2005	Grossmann I	AIChE J	v51	p1846	A	77	69
22	1994	Raman R	Comput Chem Eng	v18	p563	A	77	73
23	1988	Brooke A	Gams Users Guide			B	76	57
24	2004	Sahinidis NV	Comput Chem Eng	v28	p971	A	76	57
25	2006	Wachter A	Math Program	v106	p25	A	76	53
26	1987	Reid RC	Properties Gases Liq			B	72	48
27	1993	Shah N	Comput Chem Eng	v17	p229	A	69	66
28	1983	Kirkpatrick S	Science	v220	p671	A	68	37
29	1980	Finlayson BA	Nonlinear Anal Chem			B	66	33
30	2003	Qin SJ	Control Eng Pract	v11	p733	A	66	44
31	1986	Duran MA	AIChE J	v32	p123	A	64	59
32	1995	Pinto JM	Ind Eng Chem Res	v34	p3037	A	63	54
33	1981	Nishida N	AIChE J	v27	p321	A	62	46
34	1978	Linnhoff B	AIChE J	v24	p633	A	61	58
35	1987	Kocis GR	Ind Eng Chem Res	v26	p1869	A	60	58

36	1989	Kocis GR	Comput Chem Eng	v13	p797	A	60	55
37	2005	Benders JF	Comput Manag Sci	v2	p3	A	56	52
38	1987	Cuthrell JE	AIChE J	v33	p1257	A	56	39
39	1987	Grossmann IE	Comput Chem Eng	v11	p675	A	56	53
40	1989	El-Halwagi MM	AIChE J	v35	p1233	A	55	44

Abbreviations: TC = Total citations; A = Article; B = Book.

Table-5a List of authors who published most papers in CCE

R	Full Name	University	Country	TC	TP	H	C/P	>100	>50
1	Ignacio E. Grossmann	Carnegie Mellon U	USA	12,380	206	62	60.10	34	78
2	Stratos Pistikopoulos	Texas A&M U	USA	2,653	98	29	27.07	4	18
3	Lorenz T. Biegler	Carnegie Mellon U	USA	3,561	97	34	36.71	8	18
4	Rafiqul Gani	Technical U Denmark	DEN	2,059	83	27	24.81	3	10
5	Christodoulos A. Floudas	Texas A&M Energy Institute	USA	4,672	78	37	59.90	15	34
6	Luis Puigjaner	Polytechnic U Catalonia	ESP	1,297	68	22	19.07	1	4
7	Wolfgang Marquardt	RWTH Aachen U	GER	1,747	65	24	26.88	2	9
8	Gintaras V. (Rex) Reklaitis	Purdue U	USA	1,485	58	24	25.60	2	8
9	Antonio Espuna	Polytechnic U Catalonia	ESP	958	49	19	19.55	1	3
10	Venkat Venkatasubramanian	Columbia U	USA	2,867	48	23	59.73	4	11
11	Nilay Shah	Imperial College London	UK	1,505	45	19	33.44	4	6
12	Manfred Morari	U Pennsylvania	USA	2,071	41	19	50.51	2	7
13	Sigurd Skogestad	Norwegian U Sci Tech	NOR	1,032	41	18	25.17	1	4
14	Mark A. Stadtherr	U Illinois Urbana-Champaign	USA	653	41	15	15.93	0	2
15	José A. Romagnoli	Louisiana State U	USA	444	41	12	10.83	0	0
16	Ramesh Srinivasan	U California, Irvine	USA	1,022	40	19	25.55	1	4
17	Constantinos Pantelides	Imperial College London	UK	2,176	39	21	55.79	5	8
18	Jaehong Lee	ETH Zurich	SWI	2,064	39	18	52.92	3	8
19	Zdravko Kravanja	U Maribor	SLN	1,234	39	21	31.64	1	8
20	Arthur W. Westerberg	Carnegie Mellon U	USA	991	38	18	26.08	1	7
21	Iftekhar A Karimi	National U Singapore	SGP	668	38	17	17.58	0	2
22	Sebastian Engell	Dortmund U Technology	GER	920	37	15	24.86	1	5
23	Thomas F. Edgar	U Texas Austin	USA	855	37	16	23.11	2	2
24	Sandro Macchietto	Imperial College London	UK	702	36	16	19.50	1	3
25	Iiro Harjunkoski	ABB Corporate Res	GER	1,795	34	21	52.79	5	11
26	Angelo Lucia	U Rhode Island	USA	332	34	10	9.76	0	0
27	Serge Domenech	CNRS	FRA	443	33	13	13.42	0	0
28	Marianthi Ierapetritou	Ecolé Polytech Féd Lausanne	SWI	806	32	16	25.19	1	3
29	Jaime Cerda	U Nacional del Litoral	ARG	1,402	31	18	45.23	2	7
30	Christos T. Maravelias	U Wisconsin-Madison	USA	934	31	16	30.13	2	5
31	Fengqi You	Cornell U	USA	1,353	30	19	45.10	3	10
32	John Perkins	Imperial College London	UK	751	30	15	25.03	1	5
33	Luc Pibouleau	CNRS	FRA	370	30	11	12.33	0	0
34	Gregory Stephanopoulos	MIT	USA	1,098	28	18	39.21	2	7
35	Joseph Pekny	Purdue U	USA	908	28	17	32.43	2	5

36	David WT Rippin	ETH Zurich	SWI	771	28	16	27.54	0	6
37	Rubens Maciel	U Estadual do Oeste do Parana	BRA	484	28	10	17.29	1	2
38	Dominique Bonvin	Rutgers U	USA	846	27	12	31.33	3	4
39	David Bogle	U College London	UK	257	27	9	9.52	0	1
40	Jose Mauricio Pinto	U Sao Paulo	BRA	1,211	26	16	46.58	4	7
41	Karl Tapio Westerlund	Åbo Akademi U	FIN	664	26	14	25.54	0	4
42	Prodromos Daoutidis	U Minnesota	USA	596	26	14	22.92	0	5
43	Daniel R. Lewin	Technion Israel Inst Tech	ISR	492	26	13	18.92	1	2
44	Gunter Wozny	Technical U Berlin	GER	470	26	12	18.08	1	2
45	Eric S. Fraga	U College London	UK	256	26	9	9.85	0	0
46	Panagiotis D. Christofides	U California, Los Angeles	USA	712	25	12	28.48	1	4
47	Liang-Tseng Fan	Kansas State U	USA	462	25	12	18.48	1	2
48	Lazaros Papageorgiou	U College London	UK	629	24	12	26.21	1	4
49	Warren D. Seider	U Pennsylvania	USA	386	24	10	16.08	0	2
50	Ian Cameron	National U South / CONICET	ARG	343	24	10	14.29	0	2

Table 5b. List of top 50 influential authors in CCE

R	Author's Name	University	Country	TC (Scopus)	TP	H	C/P	>100	>50
1	Grossmann, I.E.	Carnegie Mellon U	USA	16370	206	72	79.5	46	104
2	Venkatasubramanian, V.	Columbia U	USA	5855	48	27	122.0	8	18
3	Floudas, C.A.	Texas A&M Energy Institute	USA	5769	78	41	74.0	22	35
4	Biegler, L.T.	Carnegie Mellon U	USA	4817	97	39	49.7	9	32
5	Rengaswamy, R.	IIT, Madras	India	4257	21	11	202.7	3	6
6	Kavuri, S. N.	Purdue University	USA	3895	6	6	649.2	3	3
7	Pistikopoulos, E.N.	Texas A&M U	USA	3742	98	32	38.2	8	23
8	Yin, K	University of Minnesota	USA	3049	6	6	508.2	2	2
9	Gani, R.	Technical U Denmark	Den	2976	83	32	35.9	6	18
10	Pantelides, C.C.	Imperial College London	UK	2836	39	23	72.7	7	17
11	Morari, M.	U Pennsylvania	USA	2829	41	21	69.0	3	10
12	Harjunkoski, I.	ABB Corporate Res	GER	2541	34	22	74.7	7	16
13	Marquardt, W.	RWTH Aachen U	GER	2352	65	29	36.2	6	13
14	You, F.	Cornell U	USA	2258	30	26	75.3	6	20
15	Reklaitis, G.V.	Purdue U	USA	2026	58	27	34.9	3	13
16	Qin, SJ	University of Texas at Austin	USA	2014	11	11	183.1	5	8
17	Cerdá, J.	U Nacional del Litoral	ARG	1959	31	21	63.2	6	11
18	Sahinidis, N.V.	Carnegie Mellon U	USA	1933	22	16	87.9	5	7
19	Mcavoy, TJ	University of Maryland	USA	1911	11	10	173.7	4	7
20	Downs, JJ	Eastman Chemical Company	USA	1824	3	3	608.0	1	2
21	Ierapetritou, M.G.	Ecolé Polytech Féd Lausanne	SWI	1785	32	24	55.8	4	13
22	Vogel, EF	Tennessee Eastman Company	USA	1754	2	2	877.0	1	1
23	Puigjaner, L.	Polytechnic U Catalonia	ESP	1736	68	26	25.5	1	10
24	Kravanja, Z.	U Maribor	SLN	1736	39	24	44.5	2	13
25	Pinto, J.M.	U Sao Paulo	BRA	1663	26	17	64.0	6	10
26	Shah, N.	Imperial College London	UK	1649	45	20	36.6	4	7
27	Sargent, R.W.H.	University of London	UK	1603	18	11	89.1	3	6
28	Méndez, C.A.	Carnegie Mellon U	USA	1588	22	14	72.2	6	9
29	Skogestad, S.	Norwegian U Sci Tech	NOR	1511	41	21	36.9	1	9
30	Maravelias, C.T.	U Wisconsin-Madison	USA	1462	31	20	47.2	3	8
31	Engell, S.	Dortmund U Technology	GER	1423	37	21	38.5	2	8
32	Lee, J.H.	ETH Zurich	SWI	1393	39	19	35.7	3	8
33	Srinivasan, R.	U California, Irvine	USA	1365	40	22	34.1	2	8
34	Stephanopoulos, G.	MIT	USA	1299	28	19	46.4	4	8

35	Bonvin, D.	Rutgers U	USA	1277	27	14	47.3	3	5
36	Yee, TF	Carnegie Mellon U	USA	1241	3	3	413.7	3	3
37	Espuña, A.	Polytechnic U Catalonia	ESP	1217	49	20	24.8	1	8
38	Westerberg, A.W.	Carnegie Mellon U	USA	1212	39	20	31.1	2	9
39	Edgar, T.F.	U Texas Austin	USA	1193	37	18	32.2	2	7
40	Pekny, J.F.	Purdue U	USA	1186	28	18	42.4	3	8
41	Gabrys, B	Bournemouth U Fern Barrow	UK	1179	3	3	393.0	2	2
42	Christofides, P.D.	U California, Los Angeles	USA	1051	25	15	42.0	1	4
43	Karimi, I.A.	National U Singapore	SGP	1040	38	20	27.4	0	8
44	Lin, X	Princeton University	USA	1019	5	5	203.8	4	4
45	Westerlund, T.	Åbo Akademi U	FIN	996	26	16	38.3	2	8
46	Adjiman, C.S.	Princeton University	USA	996	13	9	76.6	3	6
47	Papoulias, SA	Carnegie-Mellon U	USA	970	3	3	323.3	2	3
48	Perkins, J.D.	Imperial College London	UK	937	30	16	31.2	1	5
49	Kadlec, P	Bournemouth University	UK	935	3	3	311.7	1	2
50	Morris, A.J.	University of Newcastle	UK	930	17	12	54.7	4	8

Table 6. The most productive and influential institutions in CCE

R	University	Country	TC	TP	H	C/P	>50	>10	ARWU	QS
1	Carnegie Mellon U	USA	17113	384	68	44.57	42	104	91	47
2	Imperial College London	UK	7320	272	44	26.91	14	37	24	8
3	Purdue U	USA	6461	154	37	41.95	8	23	70	105
4	Technical U Denmark	Denmark	2675	125	28	21.40	4	12	151-200	116
5	Norwegian U Sci Tech	Norway	1907	113	24	16.88	2	7	101-150	259
6	Texas A&M U College Station	USA	1296	99	22	13.09	0	4	151-200	195
7	RWTH Aachen U	Germany	1854	93	24	19.94	2	7	201-300	141
8	U Manchester	UK	1994	91	23	21.91	6	10	34	34
9	U College London	UK	1384	91	20	15.21	1	5	17	7
10	U Toulouse	France	824	88	15	9.36	0	1	201-300	751-800
11	U Fed Toulouse Midi Pyrenees	France	809	87	15	9.30	0	1	-	-
12	Princeton U	USA	4709	86	37	54.76	16	33	6	13
13	MIT	USA	2487	85	31	29.26	4	15	4	1
14	ETH Zurich	Switzerland	2593	84	26	30.87	1	9	19	10
15	Inst National Polytech Toulouse	France	796	84	15	9.48	0	1	-	-
16	U Wisconsin Madison	USA	2129	83	25	25.65	5	8	28	55
17	Polytechnic U Catalonia	Spain	1431	82	23	17.45	1	4	-	275
18	U Texas Austin	USA	2900	81	26	35.80	9	11	40	67
19	National U Singapore	Singapore	1569	81	24	19.37	1	4	85	15
20	Dortmund U Technology	Germany	1402	80	19	17.53	1	6	-	601-650
21	Polytechnic U Milan	Italy	1279	80	18	15.99	2	3	201-300	170
22	U Estadual de Campinas	Brazil	1066	75	18	14.21	1	3	301-400	182
23	National U the South	Argentina	1003	70	18	14.33	0	3	-	-
24	National U the Littoral	Argentina	1995	68	22	29.34	3	10	-	-
25	McMaster U	Canada	1291	68	18	18.99	3	9	86	140
26	U Alberta	Canada	1325	65	18	20.38	2	6	101-150	90
27	Tsinghua U	China	939	65	18	14.45	0	3	45	25
28	U Pannonia	Hungary	857	62	14	13.82	2	4	-	-
29	U Leeds	UK	722	59	14	12.24	0	4	101-150	101
30	U Sydney	Australia	749	55	16	13.62	0	2	68	50
31	U Toulouse III Paul Sabatier	France	576	54	14	10.67	0	0	201-300	501-550
32	Northwestern U	USA	1730	53	25	32.64	2	11	25	28
33	Rutgers State U New Brunswick	USA	971	53	16	18.32	2	3	101-150	283
34	U Federal Do Rio de Janeiro	Brazil	715	53	16	13.49	0	2	301-400	311
35	U Maribor	Slovenia	1072	51	20	21.02	0	7	-	801-1000
36	Georgia Institute of Technology	USA	872	50	15	17.44	1	2	79	70

37	U Edinburgh	UK	524	49	14	10.69	0	0	32	23
38	Seoul National U	South Korea	411	49	11	8.39	0	0	101-150	36
39	U Illinois Urbana Champaign	USA	1699	47	18	36.15	3	6	41	69
40	Delft U Technology	Netherlands	692	46	15	15.04	0	4	151-200	54
41	Abo Akademi U	Finland	908	45	18	20.18	0	4	-	551-600
42	U Porto	Portugal	797	44	16	18.11	1	3	301-400	301
43	U Lisboa	Portugal	709	44	16	16.11	0	3	151-200	305
44	U California Los Angeles	USA	1102	43	18	25.63	2	4	11	33
45	Ecole Polytech Fed Lausanne	France	1206	41	17	29.41	3	6	401-500	12
46	Otto Von Guericke U	Germany	477	41	12	11.63	0	2	-	-
47	Newcastle U	UK	1190	40	21	29.75	1	10	201-300	161
48	U Waterloo	Canada	732	40	14	18.30	1	1	151-200	152
49	Zhejiang U	China	495	40	12	12.38	0	1	67	87
50	Budapest U Tech Econ	Hungary	422	40	13	10.55	0	2	-	751-800

Abbreviations are available in previous tables except for: ARWU and QS = Academic Ranking of World Universities and QS University Ranking.

Table 7. Other productive and influential institutions in CCE

R	Institution	Country	TC	TP	H	TC/TP	>100	>50
1	CONICET	Argentina	3166	161	28	19.66	3	13
2	CNRS	France	1471	148	21	9.94	0	2
3	CSIR India	India	877	56	18	15.66	0	4
4	CNRS Inst Engineering Systems Sciences	France	712	56	16	12.71	0	1
5	United States Department of Energy	USA	1079	54	19	19.98	2	4
6	Max Planck Society	Germany	482	44	10	10.95	0	3
7	Dow Chemical Company	USA	1215	41	16	29.63	4	6
8	ABB	Switzerland	1474	30	17	49.13	3	8

Table 8. The most productive institutions in CCE: Temporal evolution

R	Institution	TC	TP	R	Institution	TC	TP
	1977-1988				1999-2008		
1	Carnegie Mellon U	2718	46	1	Carnegie Mellon U	5582	101
2	U Wisconsin Madison	602	23	2	Imperial College London	2123	59
3	Washington U St Louis	220	17	3	Purdue U	4173	52
	1989-1998			4	CONICET	1649	43
1	Imperial College London	3947	135	5	U Estadual Campinas	572	42
2	Carnegie Mellon U	6277	108	6	CNRS	569	41
3	CNRS	519	65	7	U College London	783	37
4	Purdue U	1620	54	8	RWTH Aachen U	941	33
5	Norwegian U Sci Tech	562	43	9	National U Singapore	984	31
6	ETH Zurich	797	40	10	CNRS Inst Eng Syst Sci INSIS	481	31
7	U Fed Toulouse Midi Pyrenees	278	40	11	U Manchester	540	30
8	U Toulouse	278	40		2009-2018		
9	Inst National Polytech Toulouse	271	38	1	Carnegie Mellon U	2624	129
10	CONICET	397	37	2	CONICET	931	69
11	MIT	1585	36	3	Imperial College London	1006	67
12	U Manchester	1217	35	4	Texas A&M U College Station	887	67
13	U Sydney	429	35	5	Technical U Denmark	1227	60
14	Technical U Denmark	409	35	6	National U Singapore	565	44
15	Princeton U	2420	34	7	U Alberta	684	43
16	Norwegian U Sci Tech	430	31	8	Polytechnic U Milan	647	42
17	U Texas Austin	1497	30	9	RWTH Aachen U	601	42
18	Polytechnic U Catalonia	380	28	10	Norwegian U Science Tech	494	42
19	U Edinburgh	359	27	11	U Wisconsin Madison	808	38
20	Dortmund U Technology	237	26	12	McMaster U	541	38
21	U Estadual Campinas	242	23	13	Tsinghua U	511	38
22	Polytechnic U Milan	334	22	14	Purdue U	518	37
23	National U the South	192	22	15	National U the Littoral	666	36
24	U Maryland College Park	1743	21	16	USA Department of Energy	643	36
25	U Maribor	420	20	17	CNRS	339	36
26	Abo Akademi U	417	20	18	U College London	417	34
27	U Stuttgart	361	20	19	U Lisboa	492	33
28	U Pannonia	207	20	20	Ecole Polytech Fed Lausanne	656	32
29	U College London	198	20	21	Rutgers State U New Brunswick	469	32
				22	Princeton U	808	30

23	Polytechnic U Catalonia	516	30

Abbreviations are available in previous tables. Note that for the period of 1977-1988, the table only shows those universities with at least fifteen papers. For the period 1989-1998, the table shows those universities with at least twenty papers and for the last periods of 1999-2008 and 2009-2018, only those with at least thirty papers are listed.

Table 9. The most productive and influential countries in CCE

R	Country	TC	TP	H	C/P	>50	>10	Population	TC/Pop	TP/Pop
1	USA	69,148	2,352	112	29.40	129	337	328,128,000	21.07	0.72
2	UK	16,677	819	61	20.36	27	78	66,040,229	25.25	1.24
3	Germany	9,019	500	45	18.04	9	36	82,793,800	10.89	0.60
4	China	6,173	437	37	14.13	4	19	1,418,607,488	0.44	0.03
5	Canada	6,029	345	37	17.48	8	26	37,275,900	16.17	0.93
6	France	3,140	275	30	11.42	0	10	67,348,000	4.66	0.41
7	Spain	4,062	237	32	17.14	5	14	46,659,302	8.71	0.51
8	Argentina	4,108	236	31	17.41	3	17	44,494,502	9.23	0.53
9	Brazil	3,531	215	32	16.42	4	12	209,811,000	1.68	0.10
10	Italy	2,747	191	27	14.38	4	7	60,404,843	4.55	0.32
11	India	3,237	188	32	17.22	3	15	1,339,200,000	0.24	0.01
12	Japan	3,329	175	27	19.02	6	14	126,440,000	2.63	0.14
13	Australia	2,215	168	24	13.18	1	5	25,115,200	8.82	0.67
14	South Korea	2,160	165	23	13.09	3	5	51,635,256	4.18	0.32
15	Denmark	3,018	155	30	19.47	4	14	5,789,957	52.12	2.68
16	Norway	2,675	155	26	17.26	3	10	5,312,343	50.35	2.92
17	Netherlands	2,311	147	24	15.72	3	13	17,268,800	13.38	0.85
18	Switzerland	3,910	139	32	28.13	4	14	8,508,904	45.95	1.63
19	Hungary	1,537	136	19	11.30	2	6	9,771,000	15.73	1.39
20	Portugal	2,444	131	27	18.66	3	12	10,291,027	23.75	1.27
21	Finland	1,701	122	23	13.94	0	6	5,520,535	30.81	2.21
22	Mexico	1,974	121	24	16.31	1	7	119,938,473	1.65	0.10
23	Belgium	1,988	116	24	17.14	2	12	11,428,164	17.40	1.02
24	Singapore	1,830	95	26	19.26	1	5	5,638,700	32.45	1.68
25	Greece	1,629	89	24	18.30	0	8	10,768,193	15.13	0.83
26	Iran	856	80	16	10.70	0	1	81,931,500	1.04	0.10
27	South Africa	745	71	14	10.49	1	2	57,725,600	1.29	0.12
28	Slovenia	1,301	69	22	18.86	0	7	2,070,050	62.85	3.33
29	Israel	779	55	17	14.16	1	2	8,942,420	8.71	0.62
30	Sweden	846	54	15	15.67	0	5	10,196,177	8.30	0.53
31	Turkey	603	50	16	12.06	0	1	80,810,525	0.75	0.06
32	Poland	438	48	14	9.13	0	0	38,433,600	1.14	0.12
33	Czech Republic	407	47	11	8.66	0	1	10,625,449	3.83	0.44
34	Malaysia	877	44	18	19.93	0	4	32,524,300	2.70	0.14
35	Romania	796	44	15	18.09	1	5	19,524,000	4.08	0.23

36	Austria	656	43	12	15.26	1	2	8,857,960	7.41	0.49
37	Chile	400	37	13	10.81	0	0	17,574,003	2.28	0.21
38	Saudi Arabia	370	37	10	10.00	0	1	33,413,660	1.11	0.11
39	Russia	219	30	9	7.30	0	0	146,877,088	0.15	0.02
40	Thailand	197	21	7	9.38	0	1	69,183,173	0.28	0.03
41	Bulgaria	259	19	8	13.63	0	1	7,050,034	3.67	0.27
42	Colombia	176	19	6	9.26	0	1	50,025,000	0.35	0.04
43	Serbia	126	16	6	7.88	0	1	7,001,444	1.80	0.23
44	Kuwait	135	14	7	9.64	0	0	4,226,920	3.19	0.33
45	Slovakia	97	14	6	6.93	0	0	5,443,120	1.78	0.26
46	Egypt	144	13	7	11.08	0	0	97,847,700	0.15	0.01
47	Qatar	82	11	6	7.45	0	0	2,717,886	3.02	0.40
48	Venezuela	71	10	5	7.10	0	0	31,828,110	0.22	0.03
49	Philippines	213	8	6	26.63	0	2	106,719,000	0.20	0.01
50	Ireland	79	8	6	9.88	0	0	4,857,000	1.63	0.16

Abbreviations are available in previous tables except for: TP/Pop and TC/Pop = Total papers and citations per 100 thousand of inhabitants.

Table 10. Countries with the highest number of papers: Annual evolution

R	COUNTRY	Pre 99	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total
1	USA	978	66	121	30	53	56	85	79	43	25	73	54	69	63	54	73	91	66	73	98	102	2,352
2	UK	359	63	32	16	16	7	19	20	9	17	11	22	16	26	18	25	26	20	39	31	27	819
3	Germany	159	20	17	13	2	7	16	20	11	12	24	21	11	23	12	16	17	22	26	29	22	500
4	China	41	6	33	4	5	11	18	10	12	12	19	19	12	19	14	27	28	20	36	38	53	437
5	Canada	61	13	10	6	5	8	17	11	12	5	21	12	12	11	15	17	19	8	29	23	30	345
6	France	138	16	6	8	1	5	5	5	6	6	8	8	3	8	9	8	9	6	7	7	6	275
7	Spain	47	8	5	7	7	0	6	4	4	12	12	6	11	12	18	10	16	10	14	14	14	237
8	Argentina	78	12	14	6	4	6	8	5	1	4	6	9	6	11	10	13	12	8	9	8	6	236
9	Brazil	44	16	24	8	4	9	7	12	0	4	4	4	6	5	12	11	7	6	11	8	13	215
10	Italy	76	4	4	6	3	4	5	1	1	2	4	7	4	13	7	9	9	6	12	7	7	191
11	India	34	4	8	2	2	5	10	10	10	5	6	7	8	9	6	10	5	6	13	15	13	188
12	Japan	71	12	26	6	4	2	11	3	1	3	4	1	4	2	1	6	3	3	2	4	6	175
13	Australia	78	9	11	6	2	2	2	4	0	7	6	1	2	2	6	4	6	2	6	8	4	168
14	South Korea	40	12	24	3	3	2	4	2	0	1	2	0	3	2	8	5	6	10	12	10	16	165
15	Denmark	54	8	6	3	4	1	5	3	0	1	2	5	9	3	7	12	5	9	5	7	6	155
16	Norway	73	7	2	1	1	1	9	2	1	2	5	5	6	0	4	6	5	3	6	5	11	155
17	Netherlands	50	14	9	5	3	4	6	0	1	2	6	9	4	4	4	2	8	1	6	7	2	147
18	Switzerland	61	5	1	1	1	2	1	1	1	0	6	5	2	2	1	5	10	8	11	9	6	139
19	Hungary	62	22	7	4	3	0	3	6	0	0	2	5	7	3	0	4	0	4	1	3	0	136
20	Portugal	33	3	6	4	5	0	7	8	1	2	3	6	2	7	7	5	8	3	9	6	6	131
21	Finland	52	13	4	4	3	1	3	4	3	2	5	3	3	6	0	3	3	2	3	1	4	122
22	Mexico	13	5	3	0	4	3	5	5	1	5	7	5	5	9	7	3	9	8	10	9	5	121
23	Belgium	43	2	2	2	1	2	3	5	1	5	5	2	3	4	7	3	8	3	7	4	4	116
24	Singapore	6	2	2	3	4	5	4	2	2	4	6	6	3	10	4	6	5	2	4	6	9	95
25	Greece	34	2	1	1	3	1	3	1	2	1	1	3	3	7	3	5	3	2	5	1	7	89
26	Iran	3	1	1	1	0	0	0	3	2	1	7	4	2	5	5	3	5	4	5	18	10	80
27	South Africa	20	2	6	1	1	0	5	3	1	2	3	3	3	2	3	2	2	3	4	4	1	71
28	Slovenia	31	5	4	3	2	0	4	2	0	3	4	0	1	2	1	0	1	3	0	3	0	69
29	Israel	33	4	4	0	4	2	1	0	1	0	2	2	0	0	0	0	1	0	0	1	0	55
30	Sweden	21	2	1	0	1	3	1	2	2	1	1	1	1	0	2	4	1	3	3	1	3	54
31	Turkey	17	3	0	2	2	3	4	3	4	1	2	0	0	0	0	1	2	3	2	1	0	50
32	Poland	27	3	0	0	0	0	0	1	0	1	1	1	1	6	2	1	0	2	0	2	0	48
33	Czech Republic	31	2	0	2	1	0	0	2	2	0	1	0	1	2	2	0	0	0	0	1	0	47
34	Malaysia	1	0	1	0	1	0	1	4	0	2	3	0	2	2	7	5	1	6	3	3	2	44
35	Romania	11	1	1	0	1	0	0	0	0	1	1	9	1	4	2	4	0	3	2	2	1	44
36	Austria	18	4	2	0	1	0	1	1	1	0	1	1	2	0	0	1	0	2	4	1	3	43
37	Chile	4	2	2	1	0	1	1	1	0	1	3	1	1	2	3	1	4	2	4	2	1	37
38	Saudi Arabia	10	0	1	0	0	2	1	1	0	0	0	1	0	2	4	3	2	2	2	3	3	37
39	Russia	18	4	0	1	0	0	0	0	0	0	0	0	0	1	0	1	3	0	1	0	1	30
40	Thailand	0	0	0	0	0	0	0	3	0	1	1	0	0	2	1	2	1	1	2	3	4	21

Table 11. The most productive and influential super-regions in CCE

R	Region	TC	TP	H	TC/TP	>100	>50
1	North America	75,691	2,751	113	27.51	134	363
2	Europe	53,670	3,175	85	16.90	60	225
3	Asia	20,651	1,377	57	15.00	18	71
4	Central and South America	8,261	516	41	16.01	7	30
5	Middle East	2,983	268	29	11.13	1	6
6	Oceania	2,253	172	24	13.10	1	5
7	Africa	1,062	97	17	10.95	1	3

Abbreviations are available in previous tables.

Table 12. Citing articles of CCE: Authors, universities, countries and journals

Author	TP	University	TP	Country	TP	Journal	TP
Grossmann, IE	512	CNRS	1284	USA	13,703	Computers Chemical Engineering	4,915
Floudas, CA	288	Carnegie Mellon U	1125	China	13,122	Industrial Engineering Chemistry Res	4,274
Pistikopoulos, EN	287	Imperial College London	1075	UK	5,124	Computer Aided Chemical Engineering	2,538
Biegler, LT	282	Zhejiang U	1044	Germany	4,061	Chemical Engineering Science	1,939
Gani, R	269	Tsinghua U	727	Canada	3,116	Aiche Journal	1,724
Marquardt, W	247	CONICET	694	India	2,699	J Process Control	1,081
Zhang, J	233	Technical U Denmark	660	France	2,641	Chemical Engineering Research Design	962
Engell, S	195	Purdue U	629	Iran	2,480	Proc American Control Conf	671
You, FQ	187	Texas AM U College Station	628	Spain	2,265	Energy	660
Zhang, Y	186	Chinese Acad Sci	612	Italy	2,094	Ifac Papersonline	602
El-Halwagi, MM	185	USA Department of Energy	603	Brazil	2,043	Applied Thermal Engineering	517
Christofides, PD	181	Northeastern U China	591	South Korea	1,646	J Cleaner Production	512
Puigjaner, L	181	U Manchester	587	Australia	1,479	Applied Energy	486
Marechal, F	176	National U Singapore	577	Netherlands	1,346	Chemical Engineering Journal	484
Wang, Y	176	Norwegian U Sci Tech	565	Japan	1,269	Chemical Engineering Transactions	484
Liu, Y	172	MIT	555	Mexico	1,265	Chemical Engineering and Processing	428
Kravanja, Z	164	U Alberta	549	Switzerland	1,108	Chinese J Chemical Engineering	408
Ponce-Ortega, JM	160	Polytechnic U Milan	541	Malaysia	1,095	Canadian J Chemical Engineering	390
Wozny, G	156	ETH Zurich	522	Portugal	1,026	Control Engineering Practice	358
Shah, N	153	China U Petroleum	500	Argentina	977	Chemical Engineering Technology	347
Segovia-Hernandez, JG	152	U Toulouse	485	Poland	976	Chemometrics and Intelligent Laboratory Systems	346
Barton, PI	151	U College London	482	Singapore	947	IEEE Conf Decision and Control	342
Skogestad, S	148	Delft U Technology	481	Belgium	926	Powder Technology	327
Li, J	147	RWTH Aachen U	480	Denmark	896	Lecture Notes in Computer Science	316
Braatz, RD	141	East China U Sci Tech	469	Norway	839	Fluid Phase Equilibria	307
Huang, B	141	Shanghai Jiao Tong U	462	Turkey	815	Int J Production Research	298
Song, ZH	141	Dortmund U Technology	429	Finland	789	Chemical Engineering Communications	296
Espuna, A	139	U Fed Toulouse Midi Pyrenees	425	Sweden	756	European J Operational Research	282
Lee, JH	135	CSIR India	407	Greece	718	Int J Hydrogen Energy	276
Li, Y	133	Princeton U	406	Hungary	657	ISA Transactions	256
Li, P	131	Islamic Azad U	402	Romania	564	J Chemical Engineering of Japan	249
Wang, L	131	U Waterloo	396	South Africa	531	Chinese Control Conference	248
Reklaitis, GV	130	CNRS Inst Eng Syst Sci	388	Saudi Arabia	496	Korean J Chemical Engineering	245
Tan, RR	130	Tianjin U	386	Russia	462	Expert Systems With Applications	237
Srinivasan, R	128	Xi An Jiaotong U	385	Slovenia	453	Automatica	234
Papageorgiou, LG	124	U Estadual Campinas	378	Colombia	372	Chemie Ingenieur Technik	233
Wang, J	124	Indian Inst Tech Bombay	370	Austria	371	Energy Conversion And Management	231
Karimi, IA	123	Inst National Polytech Toulouse	369	Czech Republic	370	J Chromatography A	224
Zhang, L	123	U Pannonia	366	Chile	360	J Global Optimization	214
Edgar, TF	122	Max Planck Society	364	Thailand	354	Energy Fuels	203

Abbreviations are available in previous tables.

Table 13. Co-citation of journals in CCE: Global and temporal analysis

	Global			2009-2018			1999-2008			1989-1998		
R	Journal	Cit	CLS	Journal	Cit	CLS	Journal	Cit	CLS	Journal	Cit	CLS
1	Comput Chem Eng	21490	14936.81	Comput Chem Eng	11118	8087.44	Comput Chem Eng	5828	3796.2	Comput Chem Eng	3986	2536.21
2	Ind Eng Chem Res	10708	8678.05	Ind Eng Chem Res	6682	5446.27	Ind Eng Chem Res	2857	2257.44	Aiche J	2170	1712.6
3	Aiche J	10110	8471.94	Aiche J	4501	3974.45	Aiche J	2631	2162.2	Chem Eng Sci	1533	1174.08
4	Chem Eng Sci	8003	6407.05	Chem Eng Sci	3812	3122.64	Chem Eng Sci	2192	1722.21	Ind Eng Chem Res	1167	945.85
5	J Process Contr	1919	1695.46	J Process Contr	1506	1309.93	Automatica	550	463.48	Ind Eng Chem Proc Dd	407	359.04
6	Automatica	1737	1493.65	Chem Eng Res Des	1049	993.13	J Process Contr	377	349.29	Automatica	331	281.55
7	Chem Eng Res Des	1548	1465.25	Eur J Oper Res	766	690.6	IEEE T Automat Contr	357	308.51	IEEE T Automat Contr	270	232.81
8	IEEE T Automat Contr	1129	995.13	Automatica	744	655.15	Chem Eng Res Des	310	295.93	Chem Eng Prog	257	241.3
9	Math Program	1066	982.77	Comput-Aided Chem En	663	624.54	Biotechnol Bioeng	251	188.57	Ind Eng Chem Fund	204	192.83
10	Eur J Oper Res	1015	913.54	Energy	612	556.7	Can J Chem Eng	222	209.55	Chem Eng Commun	200	189.17
11	Ind Eng Chem Proc Dd	982	888.44	Chem Eng Process	610	576.67	Eur J Oper Res	217	191.07	Int J Control	198	178.54
12	Fluid Phase Equilibr	857	700.24	Math Program	595	556.8	Math Program	210	194.83	Math Program	192	170.26
13	Chem Eng Process	769	729.23	Chem Eng J	512	488.87	Int J Control	207	191.55	Can J Chem Eng	189	176.95
14	Can J Chem Eng	724	686.01	J Global Optim	497	454.31	Fluid Phase Equilibr	205	177.41	Chem Eng Res Des	180	167.65
15	Chem Eng Prog	720	682.68	Powder Technol	478	369.38	J Comput Phys	192	159.41	Biotechnol Bioeng	155	87.9
16	J Global Optim	720	651.22	Fluid Phase Equilibr	469	380.56	Ind Eng Chem Proc Dd	187	178.45	Fluid Phase Equilibr	154	118.68
17	Biotechnol Bioeng	703	557.93	Appl Therm Eng	457	418.72	Chem Eng Prog	172	164.57	Siam J Numer Anal	145	127.02
18	Comput-Aided Chem En	674	634.5	Appl Energ	446	414.16	Science	156	138.86	Chem Eng	134	107.24
19	Int J Control	643	589.74	IEEE T Automat Contr	415	378.86	J Global Optim	154	135.26	Manage Sci	117	100.34
20	Chem Eng J	642	616.24	Control Eng Pract	406	380.7	Control Eng Pract	150	138.39	Oper Res	116	104.51
21	Energy	633	573.21	Thesis	350	323.23	Chem Eng Commun	147	144.16	Chem Process Control	105	100.1
22	Powder Technol	608	473.53	Int J Hydrogen Energ	344	269.78	Manage Sci	145	135.87	J Chem Phys	103	89.44
23	Oper Res	598	555.18	J Clean Prod	330	303.31	Oper Res	136	126.49	Technometrics	97	88.82
24	Control Eng Pract	567	531.1	J Membrane Sci	329	222.96	P Natl Acad Sci Usa	128	108.58	Acm T Math Software	94	85.18
25	J Comput Phys	566	495.11	Oper Res	319	299.63	Chem Eng Process	122	118.99	Artificial Intell	94	78.27
26	Manage Sci	555	514.29	Chemometr Intell Lab	294	259.9	Ind Eng Chem Fund	121	114.56	Siam J Sci Stat Comp	92	84.09
27	Chem Eng Commun	539	520.85	J Comput Phys	293	259.98	J Membrane Sci	120	75.14	Gams Users Guide	77	76
28	Ind Eng Chem Fund	535	504.09	Biotechnol Bioeng	288	253.34	Powder Technol	115	89.92	Thesis U London	77	68.27
29	Appl Therm Eng	486	446.45	Desalination	282	197.97	J Fluid Mech	108	82.92	J Optimiz Theory App	75	71.24
30	J Membrane Sci	471	318.84	J Chromatogr A	278	193.32	J Chem Phys	107	94.06	J Phys Chem-Us	73	61.31
31	Appl Energ	449	415.8	Energ Fuel	277	260.21	Aiche S Series	105	99.82	J Electrochem Soc	72	19.38
32	Chemometr Intell Lab	441	388.37	Fuel	277	249.6	Nature	101	90.35	J Chem Eng Jpn	71	64.88
33	J Chem Phys	428	370.74	Bioresource Technol	275	242.26	Chemometr Intell Lab	96	83.95	Neural Networks	70	58.22
34	Science	407	374.1	Chem Eng Technol	275	267.09	Hydrocarb Process	93	82.71	J Global Optim	69	59.38
35	Chem Eng Technol	396	379.34	Manage Sci	255	241.43	Chem Eng J	89	86.71	Conceptual Design Ch	65	64
36	Siam J Numer Anal	371	344.62	J Power Sources	254	173.93	Chem Eng Technol	89	83.59	J Comput Phys	65	55.92
37	Thesis	366	337.53	Renew Sust Energ Rev	245	232.95	J Electrochem Soc	87	52.77	Chem Eng J Bioch Eng	63	60.95
38	J Chromatogr A	365	259.3	Comput Oper Res	244	231.44	J Chromatogr A	83	59.96	Chem Eng-New York	62	54.72
39	Technometrics	364	339.02	Can J Chem Eng	227	219.93	Biotechnol Progr	82	75.32	Robust Process Contr	60	59
40	Int J Hydrogen Energ	359	279.29	Catal Today	223	202.86	Technometrics	82	76.91	Aiche S Ser	59	55.91

Abbreviations: R = Rank; Cit = Citations; CLS = Citation link strength.

Table 14. Most common author keyword occurrences in CCE

	Global			2009-2018			1999-2008			1989-1998		
R	Keyword	Oc	Co	Keyword	Oc	Co	Keyword	Oc	Co	Keyword	Oc	Co
1	Optimization	366	288	Optimization	194	131	Optimization	111	78	Optimization	61	41
2	Simulation	168	130	Simulation	72	48	Simulation	64	43	Dynamic Simulation	39	29
3	Scheduling	141	119	Model Predictive Control	70	36	Scheduling	58	36	Process Synthesis	32	22
4	Model Predictive Control	114	73	Scheduling	64	48	Process Control	43	24	Simulation	32	21
5	Process Synthesis	112	90	Uncertainty	55	38	Genetic Algorithm	42	29	Modeling	24	15
6	Process Control	107	83	Multi-Objective Optimization	53	29	Model Predictive Control	42	20	Neural Networks	20	12
7	Uncertainty	103	85	Global Optimization	51	31	Design	36	28	Process Control	19	11
8	Modeling	100	75	Process Synthesis	47	34	Modeling	36	17	Scheduling	19	17
9	Global Optimization	94	67	Process Design	46	32	Optimisation	36	24	Process Design	18	16
10	Process Design	93	76	Dynamic Optimization	45	33	Uncertainty	36	24	Design	16	16
11	Dynamic Simulation	91	61	Process Control	45	33	Global Optimization	35	17	Distillation	15	9
12	Dynamic Optimization	82	65	CFD	43	19	Neural Networks	34	21	Batch Process	14	10
13	Minlp	80	63	MINLP	43	32	Dynamic Optimization	33	22	Data Reconciliation	14	5
14	Parameter Estimation	78	45	Parameter Estimation	41	17	Process Synthesis	33	25	Flexibility	14	12
15	Design	74	68	Modeling	40	28	Reactive Distillation	33	18	Batch Distillation	13	8
16	Distillation	71	55	Process Optimization	38	28	Distillation	31	17	Heat Integration	13	12
17	Optimisation	68	52	Mathematical Modeling	37	27	MINLP	29	20	Process Simulation	12	9
18	Reactive Distillation	68	44	MILP	37	28	Parameter Estimation	29	18	Uncertainty	12	12
19	Multi-Objective Optimization	67	42	Computational Fluid Dynamics	36	22	Process Design	29	17	Process Modeling	11	8
20	Genetic Algorithm	66	49	Heat Integration	33	19	Optimal Control	28	21	Control	10	8
21	MILP	64	54	Process Intensification	30	19	Dynamic Simulation	27	12	Modelling	10	6
22	CFD	63	28	Mixed Integer Linear Programming	27	18	Fault Diagnosis	27	21	Process Optimization	10	7
23	Neural Networks	61	46	Process Monitoring	26	12	Modelling	26	19	Reactive Distillation	10	5
24	Modelling	59	48	Process Simulation	26	16	MILP	22	18	Artificial Intelligence	9	4
25	Process Optimization	58	49	Distillation	25	15	Batch Process	21	11	Controllability	9	6
26	Fault Diagnosis	55	40	Dynamic Simulation	25	15	Control	21	16	Genetic Algorithms	9	7
27	Heat Integration	55	45	Reactive Distillation	25	10	Fault Detection	20	11	Batch Processes	8	6
28	Optimal Control	54	41	Optimisation	24	16	Supply Chain Management	19	14	Batch Reactor	8	7
29	Control	52	48	Supply Chain	24	13	Batch Distillation	18	12	Differential-Algebraic Equations	8	6
30	Computational Fluid Dynamics	51	30	Modelling	23	16	CFD	18	3	Fault Diagnosis	8	4
31	Mathematical Modeling	51	39	Real-Time Optimization	23	17	Distributed Parameter Systems	17	8	Flowsheeting	8	7
32	Batch Process	47	33	Design	22	20	Genetic Algorithms	17	13	Global Optimization	8	3
33	Process Simulation	47	30	Process Integration	22	17	Nonlinear Control	17	12	MINLP	8	8
34	Process Monitoring	45	29	Robust Optimization	22	9	Principal Component Analysis	17	12	Nonlinear Control	8	5
35	Data Reconciliation	43	24	Sensitivity Analysis	22	13	Synthesis	17	14	Optimisation	8	6
36	Mathematical Programming	40	31	Control	21	18	Mathematical Programming	16	10	Parameter Estimation	8	4
37	Nonlinear Programming	40	35	Crystallization	21	11	Process Monitoring	16	12	Simulated Annealing	8	3
38	Fault Detection	39	28	Mixed-Integer Linear Programming	21	8	Data Reconciliation	15	7	Synthesis	8	6
39	Supply Chain Management	39	30	Nonlinear Programming	21	14	Nonlinear Systems	15	9	Energy Integration	7	5
40	Mixed Integer Linear Programming	38	29	Stochastic Programming	21	14	Artificial Neural Networks	14	9	Expert System	7	5

Abbreviations: R = Rank; Oc = Author keyword occurrences; Co = Author keyword co-occurrences links.