CRITICAL REVIEW

A bibliometric investigation of life cycle assessment research in the web of science databases

Haibin Chen · Yu Yang · Yan Yang · Wei Jiang · Jingcheng Zhou

Abstract

Purpose Over the past few decades, life cycle assessment (LCA) methodologies have been developed extensively, and there has been a growing interest in LCA research. However, as attested by scientific literature, few systematic, synthesizing, and visualizing studies have been found on LCA research which show how this field has evolved over time. The goal of this mainly bibliometric, empirical study is to get insight into publication performance of global LCA research, characterize its intellectual structure, and trace its evolution by using the bibliometric method with visual mapping.

Methods Based on the data from the ISI Web of Science databases Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Conference Proceedings Citation Index—Science (CPCI-S) and Conference Proceedings Citation Index —Social Science & Humanities (CPCI-SSH) in the period of 1998–2013, bibliometric methods are used to investigate general development profiles of LCA research, while knowledge domain visualization technologies are employed to conduct a further co-citation analysis.

Results and discussion The results and discussions of this research mainly shed light on (1) basic statistics of significant publication performances, (2) research focuses and their intellectual base in LCA research, (3) how the streams of research evolved during the whole period of interest.

Conclusions A new work on systematic and synthesizing study is conducted in this research to evaluate and map LCA research-related context. Some salient scholarly journals and

institutions are identified that have shown a significant impact during the exponential growth of LCA research in the past 16 years. Biofuel, process design, solid waste management, and livestock production-related LCA researches are the main areas where interest is surging, confirmed by the active citers in each specialty. Furthermore, from the perspective of science mapping, evolution of LCA research is traced and some pivot publications are identified, which work as structural holes for the LCA-research development in the given time window.

Keywords Bibliometrics · Evolution · Intellectual structure · LCA · Web of Science

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1 Introduction

Life cycle assessment (LCA) is a tool to assess the potential environmental impacts and resources used throughout a product's life cycle, i.e., from raw material acquisition, via production and use phases, to waste management (ISO 2006). Since its origin in the late 1960s (Liu and Müller 2012), it has been widely used in many fields, e.g., environmental management, industrial manufacturing, military systems, and tourism by industries, governmental agencies, and other organizations as a robust tool for assessing environmental impacts and resource depletion attributable to a specific product (goods or services (ISO 2006)). Over the past decades, LCA methodologies have been developed over time and made a steady progress of evolution along with their popularity, and now governments all over the world encourage the use of LCA (Guinée et al. 2011).

At the early beginning, LCA-like work started for some particular research areas, like energy analysis in Europe (Boustead 1972). In 1984, the Swiss Federal Laboratories for Materials Testing and Research (EMPA) conducted research that extended the inventory analysis and introduced

an impact assessment method (BUS 1984), catalyzing the implementation of LCA. During the period of 1970–1990, there was little public attention and very little written about LCA (Hunt and Franklin 1996). The 1990s, a period which could be regarded as the formative years of LCA, saw a remarkable growth of scientific and coordination activities worldwide (Guinée et al. 2011). Considerable efforts had been made during this period by the Society of Environmental Toxicology and Chemistry (SETAC) and the International Organization for Standardization (ISO) as well as numbers of workshops and forums to accelerate the systematization and standardization of the methodology framework of LCA. The SETAC "Code of Practice" of 1993 (Consoli et al. 1993) and ISO 14040 series of 1998 are considered pertinent. Underlying the basic structure of LCA filed by SETAC-reports, ISO 14040 defined four key phases in an LCA study, and created a standard for LCA methodology that was flexible but not detailed: "there is no single method for conducting LCA" (ISO 2006). In the 21st century, LCA is still undergoing vigorous development with several international initiatives, including the Life Cycle Initiative (UNEP 2002) and the European Platform on LCA (European Commission 2008). With the increasing demand on sustainability, diverse LCA or life-cycle based methods have been developed from 2000 on. Several carbon footprint standards have been established, also life cycle costing (LCC), first used in the mid-1960s by the U.S. Department of Defense for the acquisition of high-cost military equipment (Sherif and Kolarik 1981), is under development in an environmental context as a method on its own. More importantly, a framework for life cycle sustainability analysis (LCSA), which integrates LCA, LCC, and S-LCA (social life cycle assessment) in a single framework under the guidance of sustainability principles, has been established in the CALCAS (EU 6th Framework Co-ordination Action for Innovation in Life-Cycle Analysis for Sustainability) project which was commissioned by the European Commission in 2006 (Zamagni et al. 2009), directing the development of future LCA.

Great progress and achievements have been made in the course of the history of LCA both in theory and practice by a large number of organizations, researchers, and journals. Some articles have summarized such achievements. For instance, Finnveden et al. (Finnveden et al. 2009) reviewed recent developments in LCA methods. Peters (Peters 2009) reviewed LCA publications by Australian authors to examine the contribution made to the LCA development by Australian industry and government. Some provided a general overview of development history (see Guinée et al. 2011; Russell et al. 2005). However, there have been few efforts on systematic, chronological, and synthesizing studies to map LCA research related context. In order to understand the major themes of the research field of LCA and figure out such questions as what is the research trend? What landmark publications influenced the development of LCA the most? How has the field evolved over time? and so on. To this end, a comprehensive bibliometric analysis, focusing on all relevant peer-reviewed articles devoted to LCA was performed. Specific efforts are made in this paper to (1) summarize significant publication performances in LCA research with basic statistics, such as the chronological distribution of articles, the most relevant scientific journals and institutions, (2) identify the research focuses and the intellectual bases of them in the history of LCA research and (3) trace the evolution of LCA research over the last 16 years.

2 Methodology

2.1 Methods

Bibliometrics Bibliometrics is a set of methods to quantitatively analyze scientific and technological literature (Bellis 2009). It is generally recognized by most historians that bibliometrics owes its systematic development mainly to Price DJD and Garfield E as founders (Godin 2006), but the term "bibliometrics" was first used by Alan Pritchard (1969) in his paper *Statistical Bibliography or Bibliometrics?* published in the *Journal of Documentation* in 1969 which defined as the application of mathematics and statistical methods to books and other media of communication. A more unambiguous definition given by White and McCain (1989) is that bibliometrics is the quantitative study of literatures as reflected in bibliographies; its task is to provide evolutionary models of science, technology, and scholarship.

Bibliometrics delineates the body of research by making a measurement of items of physical units of publications, bibliographic citations, etc. (Broadus 1987). Both citation analysis and co-citation analysis are the common practical use of bibliometric methodology in evaluating research performance. Due to the complex citing behavior, there has been much debate about the value of citation analysis as a means to assess the impact of research. However, there is sufficient evidence that reference motives are not so different or "randomly given" to such an extent that the phenomenon of citation would lose its role as a reliable measure of impact. Citation analysis can yield in many situations a strong indicator of scientific performance when applied to the entire work (Van Raan 2005).

Co-citation analysis Co-citation is the frequency with which two items of earlier literature are cited together by the later literature (Small 1973). It indicates the correlation between the documents, the more co-citations two documents receive, the higher their co-citation strength, and the more likely they are semantically related (Small 1973).

Co-citation analysis is a particular form of citation, which can provide a usefully accurate picture of the intellectual nature of the specialty, the rate and direction of its evolution, and the number and identity of its key people (Garfield 1979). The work of Boyack and Klavans (2010) suggested that co-citation analysis method performs better than direct citation analysis approach, when comparing the accuracy of different mapping approaches at the scale of millions of articles. Many science mapping techniques are originated from the idea of co-citation analysis, which characterize the structure of intellectual knowledge in terms of networks of co-cited references (Small 1973). In fact, co-citation analysis is one of the most common and efficient tools for identifying central articles in a body of literature (Zitt and Bassecoulard 1994). Some of such points will have to be further elaborated as we go along. In the work of this paper, a visualization tool is employed with the intent to explore the structure and dynamics of co-citation network.

There are two forms of co-citation analysis: author co-citation analysis and document co-citation analysis. The document co-citation approach allows a fairly reliable statement as to how wide-ranging an author's documents are (Gmür 2003). This study focuses on document co-citation analysis, with a primary goal of identifying the intellectual structure of LCA research in terms of the groupings formed by accumulated co-citation trails in scientific literature.

2.2 Data

The ISI Web of Science (WoS) published by Thomson Reuters is considered to be the most important source of data for bibliometric analysis in the sciences (van Leeuwen 2006). Compared with other databases such as Scopus, its records are more consistent and standardized (Bettencourt and Kaur 2011), allowing us to extract title text and author names, more importantly, cited references for our bibliometric research. Moreover, WoS has a broad scope of the LCA relevant journals and multiple types of literature covered. Therefore, we choose WoS as the data source for our research in this paper. Results from LCA research are not presented only in scientific journals (Russell et al. 2005); many international conferences on LCA, such as meetings of the European and North American branch of SETAC, the Ecobalance conferences, etc., are also important platforms for LCA discussion, especially during the formative years. So besides sub-field databases Science Citation Index Expanded (SCI-EXPANDED) and Social Sciences Citation Index (SSCI), Conference Proceedings Citation Index—Science (CPCI-S) and Conference Proceedings Citation Index—Social Science & Humanities (CPCI-SSH) were also used as the data sources in this paper. The search strategy used to retrieve the data on LCA was as follows:

TS=("life cycle assessment*" OR "life cycle analys*" OR "life cycle sustainability assessment*" OR "life cycle sustainability analys*" OR ("eco balanc*" OR "ecobalanc*")). Timespan=1998–2013. Databases=(SCI-EXPANDED, SSCI, CPCI-S, CPCI-SSH). The retrieval time was 2014.03.31. TS was referred to as a topic search (i.e., search in the title, keywords, and abstract fields of a publication).

Our focus is on those studies related to fuller environmental life cycle assessment including an impact assessment other than a total of life cycle based, so "life cycle costing", "life cycle management" and "life cycle thinking" were excluded from the search string. Publications published in English of all document types were selected. Although publications in English only is a limitation, it represents by far the largest component of the scholarly literature, ensures consistency of records, and facilitates automatic text parsing (Bettencourt and Kaur 2011). A total of 7,782 records matched the above mentioned filtering criteria. All of them were as the main data source for further bibliometric analysis in this paper.

2.3 Process

To better interpret the bibliometric map and show the analytic results visually so as to get clear answers within the science research context, specialized software HistCite (Garfield 2004) was utilized complementing CiteSpace software (Chen 2004, 2006). Citation analysis was carried out by text-based HistCite whereas the co-citation studies described below were conducted using the CiteSpace system. HistCite uses citation counts for its bibliometric calculations. The output of HistCite can be "used to help the searcher quickly identify the most significant work on a topic and trace its year-by-year historical development" (Garfield 2004). The java application of CiteSpace visualizes co-citation in the form of increased clarity of associative networks and adopts the spectral clustering technique to aggregate nodes of strong links into groups or clusters. Such strong-linked nodes very probably come from the same field, so a cluster represents a specialty. By setting proper parameter for each function, CiteSpace can act as an ideal application for visualizing and analyzing emerging trends and changes in scientific literature, which may be in line with our expectations.

3 Results and discussion

3.1 Chronological distribution

The growing pattern of LCA research in the last 16 years (1998–2013) is shown in Fig. 1. The exponential growth can be clearly seen ($R2=0.9833$). It is found from the chronological distribution over time of those publications that year 2001
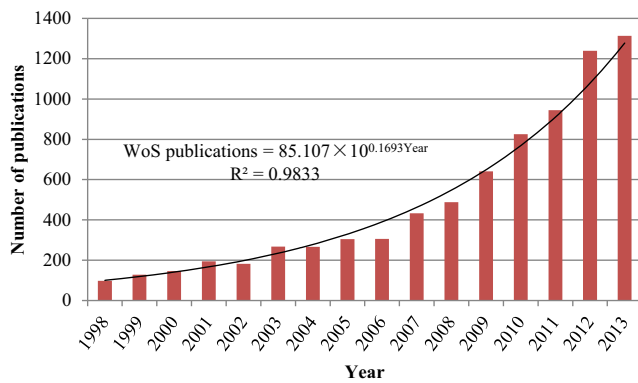
Fig. 1 Chronological distribution of life cycle assessment research-related articles in Web of Science (1998–2013)

was a turning point in the yearly publishing quantity of LCA. As Guinée (Guinée et al. 2011) mentioned, period 1990–2000 is the decade of standardization, a period of concentrated methodological development. Since 2001, LCA has been more broadly applied in practice in many fields, resulting in the increase in publications.

Overall, it is apparent from the graph that the number of publications in a related field presents a slow growth until 2006. Since 2006, the annual number of publications has grown exponentially, along with the revised edition of LCA standards brought out by ISO in 2006, which promoted the process of life impact evaluation and advanced relative research to a certain extent. During the past 16 years, WoS papers on LCA research have been turned out in a range from 98 in 1998 to 1313 in 2013, adding over 100 articles every year from the year 2008 on.

3.2 Distribution by source title

Research output of LCA is disseminated through over 1,000 sources, the majority of which are journals. The "scattering" or "productivity distributions" of articles on LCA among such sources follows Bradford's law, which is a pattern that describes the exponentially diminishing return of extending a search for references in science journals. In 1934, Bradford explained that a few journals contribute a large number of references, more journals contribute fewer and so on in a monotonic sequence ending with a large number of journals contributing one article each (Hubert 1977).

There were 5,590 articles published in academic journals and 1,926 proceedings papers in the collection. Table 1 displays a list of top 11 most productive journals with more than 100 articles. These top journals covered 33.76 %, or 2627 out of 7782 LCA research articles, indicating a pattern of high concentration of LCA research publications. Meanwhile, Table 1 demonstrates the dominance of the *International Journal of Life Cycle Assessment*. As the first journal devoted entirely to LCA, it takes up to 9.56 %. The second largest producer is

the *Journal of Cleaner Production*, with a share of 6.30 %. *Environmental Science & Technology* ranked third with a share of 3.84 %. Interestingly, these three journals also ranked as top three in both TLCS and TGCS in sequence, demonstrating their significant influence in the field of LCA research. Impact factor (IF), frequently used as a proxy for the relative importance of a journal within its field, is a good existing technique for scientific evaluation (Hoeffel 1998), but it seems that a high IF does not mean a high rank for a journal in this collection That is to say, a journal with the highest impact factor did not collect most publications, though it is deemed to be more important than those with lower ones. This may be explained by the fact that most such journals cover a broad number of domains, not just the field of LCA research. On this ground, the *International Journal of Life Cycle Assessment* has established its supremacy in the LCA research domain among those similar journals with an equivalent IF.

Besides such well-known academic journals, conferences and related meetings are also an important platform for discussions on LCAs in the course of its development, especially during the formative years, i.e., in the 1990s. Three important conferences are *International Symposium on Electronics and the Environment*, *International Symposium on Sustainable Systems and Technology*, *International Symposium on Environmentally Conscious Design and Inverse Manufacturing*. Combined, they collected a total of 240 (93, 76, 71, respectively) conference papers published in WoS.

In the major authors' choices of publications, it can be found that these top 11 journals, especially the three journals mentioned above, are recognized as the most adequate platform for academic exchange as well as the best indicator to track the field of LCA research.

3.3 Institutions of publication

The top 14 institutions with a paper quantity of more than 60 were ranked by their published articles, as shown in Table 2. It can be seen from the table that the Technical University of Denmark in Denmark has published 159 publications ranked first, as the leading institution in article quantity; It also got the highest LCS and GCS. But when compared by ALCS, Leiden University in Netherlands shows dominance in article quality with an ALCS of 21.0. Following Technical University of Denmark, University of California, Berkeley, and University of Michigan perform well with 121 and 90 publications, respectively. Notable among these institutions are the ones getting an ALCS of above 7, like Technical University of Denmark, ETH-Zürich (Swiss Federal Institute of Technology in Zurich), University of California, Berkeley, Carnegie Mellon University, and Norwegian University of Science and Technology besides Leiden University, suggesting high quality papers published by them. The papers in the collection

Table 1 Top 11 most productive Web of Science journals with a yearly paper quantity of more than 100 on LCA research

No.	Journal	Recs	%	LCS	GCS	IF
1	International Journal of Life Cycle Assessment	744	9.56	5562	8425	3.550
2	Journal Of Cleaner Production	490	6.30	2569	5827	3.587
3	Environmental Science & Technology	299	3.84	2720	5758	5.865
4	Journal Of Industrial Ecology	210	2.70	879	1810	3.424
5	Resources Conservation and Recycling	163	2.09	1162	2589	2.889
6	Waste Management	142	1.82	1018	1982	2.926
7	Energy	134	1.72	836	2154	4.107
8	Energy Policy	120	1.54	464	1388	3.382
9	Renewable & Sustainable Energy Reviews	117	1.50	494	1884	6.577
10	Biomass & Bioenergy	106	1.36	782	2310	3.931
11	Applied Energy	102	1.31	508	1647	4.783

Recs number of articles, *LCS* local citation score, which is the number of times cited by other papers in the local collection, provided by HistCite, *GCS* global citation score, which is the citation frequency based on the full WoS count at the time the data was download, provided by HistCite, *%* percentage of articles, *IF* 5-year impact factor of the academic journal, indexed in the Journal Citation Reports 2012

have predominantly come from research institutions in the US and Spain.

3.4 Intellectual structure

Since its origination, LCA methodology has been continuously improved and found increasing wide applications in various domains. It is essential to investigate the intellectual structure of the LCA research field so as to have much more clarity about its developing trace and tendency. The intellectual structure of the LCA field is conceptualized and visualized as a time-variant duality by two fundamental concepts in information science in this paper: research front and

intellectual base. A research front is defined as an emergent and transient grouping of concepts and underlying research issues which can represent a research focus in a short period. The intellectual base of a research front is an evolving network of scientific publications cited by research-front concepts (Chen 2006). So the datasets consisting of those highly cited publications construct the intellectual base of the LCA research field. In this section, we conduct a co-citation analysis to showing the intellectual structure of LCA research by employing the CiteSpace. In CiteSpace, a research front is based on the burst terms extracted from titles, abstracts, descriptors, and identifiers of bibliographic records. We first detected a total of 230 burst terms within the top 50 most

Table 2 Most productive research institutions of WoS articles with more than 60 publications

No.	Institution	Recs	LCS	GCS	ALCS	Country
1	Tech Univ Denmark	159	1509	2783	9.5	Denmark
2	Univ Calif Berkeley	121	922	2299	7.6	US
3	Univ Michigan	90	590	1418	6.6	US
4	Univ Tokyo	86	202	538	2.3	Japan
5	ETH	84	838	1519	10.0	Swiss
6	Univ Santiago de Compostela	82	408	898	5.0	Spain
7	Carnegie Mellon Univ	81	612	1680	7.6	US
8	Univ Autonoma Barcelona	79	312	812	3.9	Spain
9	Leiden Univ	70	1472	2219	21.0	Netherlands
10	Univ Rovira & Virgili	70	367	875	5.2	Spain
11	INRA	65	359	1231	5.5	France
12	Norwegian Univ Sci & Technol	64	470	819	7.3	Norway
13	Chalmers	63	263	494	4.2	Sweden
14	US EPA	63	332	852	5.3	US

Recs number of articles, *LCS* local citation score, which is the number of times cited by other papers in the local collection, provided by HistCite, *GCS* global citation score, which is the citation frequency based on the full WoS count at the time the data was download, provided by HistCite, *ALCS* average citation frequency of a article

cited articles in each of the 16 one-year time slices between 1998 and 2013.

CiteSpace uses a time-slicing mechanism to generate a synthesized network visualization based on a series of snapshots of the evolving network across consecutive time slices. In this study, each time slice constructed a co-citation network, then the sixteen corresponding networks were subsequently synthesized into a panoramic network. To improve the clarity of a visualized network, we simplified the network by pruning (i.e., link reduction or network scaling) (see Chen 2006), then we constructed a merged network of co-cited references and burst terms which contains 692 nodes and 2,031 links (Fig. 2). Each node in the network represented as concentric ring in the network depicts a publication, where the number of citations is proportional to the thickness of a ring. The links between nodes stand for co-citation of the nodes while the colors of links between nodes indicate the first year co-citation occurred. A purple ring around a node indicates that the degree of its betweenness centrality is above 0.01, which is a measure of transformative potential for a node. Thickness of the purple ring is proportionate to the node's betweenness centrality. Ring in red suggests the occurrence of citation bursts, through which we can trace the development of research hotspots.

The merged network was divided into 26 clusters of various sizes by CiteSpace automatically. A cluster mentioned here refers to a group of co-cited references with tight connections within the same cluster, which can be seen as a specialty in a certain domain. Each cluster is labeled by the log-likelihood ratio (LLR) test method automatically. By analyzing the nature of clusters and the feature nodes in them, we can get our thought of intellectual structure into shape (Fig. 2). Table 3 summarizes the 26 clusters and lists the 10 largest ones in terms of the number of references. It is clearly found that references are unevenly distributed in clusters. These 10 largest clusters cover 70.23 % of the total set of 692. The largest clusters have 89 members taking a percentage of up to 12.86 %. By comparison, each of the five smallest clusters contains only two members.

Parameter silhouette is used here to evaluate the quality of a cluster. The silhouette shows which objects lie well within their cluster, and which ones are merely somewhere in between clusters (Rousseeuw 1987). The silhouette value of clusters ranges from −1 to 1, the value of 1 indicates a complete separation from other clusters. The obtained merged network's overall mean silhouette is 0.2568, showing a rather heterogeneous structure. However, the first 26 clusters all have an ideal silhouette value between 0.811 and 1. Labels of each cluster have a deeper connotation, and we will interpret them in detail in the following discussion. The modularity is the number of edges falling within groups minus the expected number in an equivalent network with edges placed at random (Newman 2006). So as a measure of network structure, the modularity measure of the network generated is

0.8282, suggesting dense intercluster connections between the nodes but sparse connections between nodes in different clusters.

In the merged network, co-cited nodes are grouped into a cluster of high-density areas, constituting the intellectual base of research domains. By searching the research fronts and the corresponding intellectual bases, we identified the intellectual structure of LCA research; specifically, we analyzed two aspects of a specialty: (1) themes identified by the bursting terms and active citing references in a cluster as research fronts and (2) prominent members of a cluster as the intellectual base. From the visualized work of Fig. 2, it can be observed clearly that the LCA research map has four prominent clusters: (a) cluster A (C_A, cluster 0 in the Table 3) is biofuel; (b) cluster B (C_B, cluster 1) is design related to process optimization; (c) Cluster C (C_C, cluster 2) is waste incineration in solid waste management; (d) cluster D (C_D, cluster 3) is livestock production. Table 4 lists the top three most active citing and cited publications in the first four clusters.

C_A represents the specialty on application of LCA in biofuel production, containing active citers Singh et al. (2010), Yan et al. (2010), Bai et al. (2010), etc. Alternative fuels, transportation fuels especially, are projected to grow substantially due to increasing gasoline prices, energy security concerns and negative environmental burdens. Biofuel for transport, which is converted mostly from cellulosic feedstocks, is of a great interest as one such alternative to reduce greenhouse gases (GHG) emissions as well as to decrease dependence on fossil fuels. Governments worldwide are promoting the development of biofuels (Delucchi 2010). To ascertain optimal biofuel strategies, it is necessary to take into account environmental impacts from cradle to grave (Singh et al. (2010). In this context, LCA methodology to assess the environmental impact has been usually employed to assist some improvements in the production chain since the 21st century. The specialty of C_A can be further verified by the research-front term biodiesel-production and energy-crops, which represent the derivative research of biofuel research. C_A includes intellectual-base articles such as Fargione et al. (2008), Searchinger et al. (2008), and Farrell et al. (2006). The three articles that published in Science are related to the estimation of GHG emissions from biofuel and environmental effects of biofuel production. Figure 3 shows the citation history of these cited articles. It can be seen clearly that they attracted much attention since publication, demonstrating their great role in leading the follow-up studies.

The biofuel cluster is prominent in the bibliographic landscape generated from the dataset. In hindsight, this is not a surprise considering the content of LCA. The energy input is an important index to compile a complete inventory of LCA, and energy use is always a main concern in LCA. At the very beginning, LCA studies began and developed with concerns on energy as an ecological issue. Afterward, because of the

Fig. 2 A 692-node hybrid network of co-cited articles on LCA research (1998–2013) based on 16 two-year slices. The four most prominent (i.e., largest size) clusters now present in the visualization (time taken=19 s)
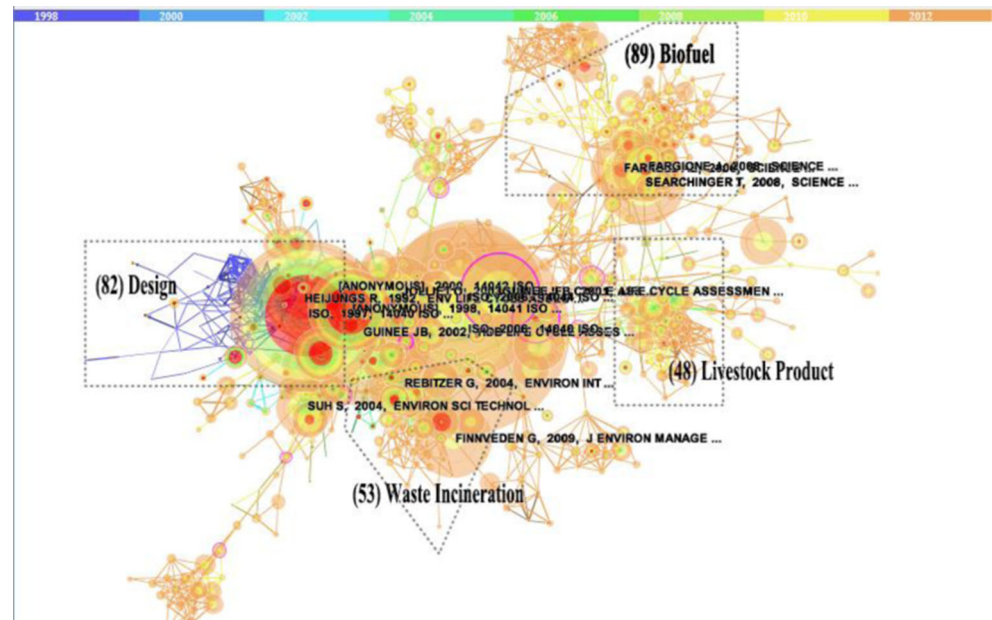
energy crisis during the formative years of LCA, there was intense interest in the energy portions of LCA (Hunt and Franklin 1996). Under the pressure of energy security and anthropogenic climate change associated with GHG emissions, the development of biofuels is of rapidly growing interest. Now, this area of research is of significant interest worldwide, and studies on biofuels continue to be conducted (von Blottnitz and Curran 2007), which makes the biofuel cluster the major one among all the clusters detected.

Titled by design, C_B is mainly about the application of LCA for product/process design/optimization. The mean year of C_B is 1996, indicating some concentrate researches of design in the late 1990s. There are numerous burst terms in this cluster, such as *life-cycle-analysis/assessments*, *sustainable-development*, *service-life*, *product-life-cycle*, *product-development*, *manufacturing-processes*, and so on. Through the analysis of these terms, it is found that the research front

detected in C_B concern about the modification or change in the design and production processes for the complete system (life cycle of the process) by considering the environmental soundness as one of the important parameters. Furthermore, the three most important citing articles in C_B, Ritzén and Norell (1999), Gungor and Gupta (1999), and Khan et al. (2001), echo with the burst terms, all of which are bound up with environmental consciousness in manufacturing and product development. The stars of intellectual-base publications in C_B are ISO 1997 (14040), a top-ranked item by bursts, as well as ISO 1998 (14041), ISO 2000 (14042), Heijungs et al. (1992), and Wenzel et al. (1997), which provide technical frameworks for process design to assess environmental impact or help reduce interventions to the environment. For example,

Table 3 The 10 largest clusters sorted by size

Cluster	Size	%	S	Label (LLR)	Year
0	89	12.86	0.824	Biofuel	2007
1	82	11.85	0.882	Design	1996
2	53	7.66	0.893	Waste incineration	2006
3	48	6.94	0.948	Livestock product	2007
4	44	6.36	0.852	Galicia	2006
5	41	5.92	0.930	Electric vehicle	2003
6	37	5.35	0.829	Resource consumption	2005
7	34	4.91	0.811	Human health	2002
8	31	4.48	0.903	Non-wood pulp mill	2006
9	27	3.90	0.949	Photovoltaic system	2006

S silhouette, *%* percentage of clusters

Table 4 The top three most active citing and cited publications in the first four clusters

| Cluster	Cited publications	Cited publications
C_A	Singh et al. 2010	Fargione et al. 2008
	Yan et al. 2010	Searchinger et al. 2008
	Bai et al. 2010	Farrell et al. 2006
C_B	Ritzén and Norell 1999	ISO (1997)
	Gungor and Gupta 1999	ISO (1998)
	Khan et al. 2001	ISO (2000)
C_C	Ghinea and Gavrilescu 2010	Finnveden et al. 2009
	Bovea et al. 2010	Reap et al. 2008
	Rigamonti et al. 2010	Rebitzer et al. 2004
C_D	de Vries and de Boer 2010	Cederberg and Stadig 2003
	Peters et al. 2010	Thomassen et al. 2008
	Martin et al. 2010	Haas et al. 2001
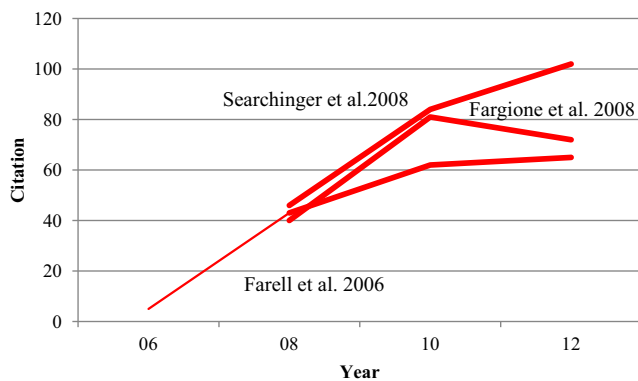
Fig. 3 The burst of citations to three intellectual-base publications in C_A. The *bold line* represents the period when burst occurred

Heijungs suggested a problem-oriented method for the identification and quantification of environmental impacts in the CML guide for LCA, while Wenzel H provided an approach to environmental design of industrial products (EDIP) 97. These salient publications published during the formative years of LCA promoted the methodological development as well as guided integration with other analytical techniques.

The design cluster is also largely revealed in this study. Under a common wider concept title, there are lots of conceptually broad burst terms in this cluster, suggesting that research activities are collectively at the center of these publications' primary focus. The 1990s witnessed a dramatic increase in the environmental consciousness worldwide, and the increase in environmental consciousness has had a profound effect on consumer behavior, with the green product market expanding at a remarkable rate (Schlegelmilch et al. 1996). Under this background, the ideas of waste minimization (or non-waste) and pollution prevention have become everyday language in the process industry and manufacturing industry. One of the key points of such pollution prevention is the systematic quantification of the environmental impact of process systems and product manufacturing, which fall into the field of LCA.

C_C gives special attention to the application of LCA to the field of solid waste management. Solid waste management is known to be an important contributor to many different environmental problems, such as climate change, stratospheric ozone depletion, human health damages, etc. (Laurent et al. 2013). These environmental pressures call for more environmentally sound management systems of solid waste. And LCA, an efficient decision-support tool for quantifying environmental impacts of systems, has been demonstrated to provide valuable inputs to identify appropriate solutions for managing solid waste (Saner et al. 2012). In this cluster, only one research-front term *heavy-metals* was found. Ghinea and Gavrilescu (2010), Bovea et al. (2010), Rigamonti et al. (2010) are among the most active citers' list. *Heavy-metals* are related to the treatment sector in a solid waste management

system; They are found in incineration residues like bottom and fly ash (Nowak et al. 2013), in municipal solid waste compost product (Plaza et al. 2000), and in landfill leachate (Christensen et al. 2001). Three citers mainly discuss LCA-based decision support models applied to alternative waste management strategies for sustainability assessment. Three review articles, Finnveden et al. (2009), Reap et al. (2008) and Rebitzer et al. (2004) are the leading publications that form the intellectual base of this specialty.

The network shows a strong connection between the design cluster and the solid waste management one, which is set beside the former cluster. Traditionally, LCA has been product focused (Khan et al. 2001), but it can also be applied to services, e.g., solid waste treatment, just like its application in the improvement of the performance of a process facility in design cluster. Solid waste has always been a focus of LCA research. Early in 1980s, solid waste was a key driving force to numerous activities in REPA (REPA, a historical term for the early environmental life cycle studies which has been used since 1970) in the USA (Hunt and Franklin 1996). REPA/LCA has been used to assess the environmental and other impacts of the implementation of waste reduction alternatives or alternative solid waste management strategies as an input to decision-making.

C_D represents the specialty that is concerned with the assessment of environmental impact by livestock production. Livestock industries are considered as an important source of GHG emissions. According to the Food and Agriculture Organization, the world's livestock sector is responsible for 18 % of the global GHG emission (de Vries and de Boer 2010). The production of GHG from livestock and their impact on climate changes are a major concern worldwide (Steinfeld et al. 2006). Given the significant contribution of livestock industries to GHG emissions profile, it is necessary to enhance the environmental performance of livestock industries. LCAs have been the subject of intense investigation to assess the environmental impact of livestock products in this industry widely. For instance, they have been conducted on pork (Eriksson 2005), lamb and beef (Schlich and Fleissner 2005), especially on milk and dairy products (Cederberg and Mattsson 2000). As to the active citers in C_D, de Vries and de Boer (2010), Peters et al. (2010), and Martin et al. (2010) examined the environmental consequences of livestock product using LCA. Burst terms *GHG-emissions*, *production-systems*, *feed-production* related to livestock production and its environmental impacts are detected which is fitting with the context of the citers. Other than Cederberg and Stadig (2003) and Thomassen et al. (2008), which dealt with LCAs of milk production, intellectual-base article Haas et al. (2001) assessed the environmental impacts of grassland farms.

It could be found that though falling into one research field, research fronts do not always share the same topic with their intellectual bases. In fact, a research front may be a detailed

and intensive study of its intellectual base; it also could be inspired by the intellectual base and go in another direction.

Our survey has revealed the intellectual structure of the research landscape relevant to LCA. It also raises some questions that our methodology is unlikely to be able to answer. For example, in each cluster constructed by cited reference, what is the proportion of the citation of affirmational/ negational type? Citing behavior is much complicated, not every citing work confirms cited work (Bornmann and Daniel 2008). Those works that hold the critical view in a detected cluster or specialty is, however, hard to distinguish by this document co-citation analysis research. And why some topics have apparently attracted more research attention than others? Say, references are unevenly distributed in clusters, making a clear size variation of clusters, and it is hard to discover the root cause for this in the paper.

3.5 Evolution

Figure 4 shows a timeline visualization of the 26 distinct co-citation clusters, from which we can easily trace the evolution of research focuses in LCA studies over time. Each cluster was plotted horizontally alone timelines with its label displayed to the right. We are particularly interested in the nodes with a purple ring, for the importance of these nodes in the network in connecting individual nodes and co-citation clusters. By exploring the pivotal nodes that connect different clusters, and analyzing the temporal distribution characteristics of each cluster, evolution the pathways of LCA research can be revealed.

The timeline visualization graph shows that the earlier publications, e.g., Leontief (1970), Keeney (1976), Bullard (1978) and Boustead and Hancock (1979), obtain multi-period citations, and present stable intellectual bases for the long-term development in LCA research. On the whole of the network, the 26 clusters could be divided into two groups. One group contains the upper 13 clusters of the 26 clusters (group A), and the 13 clusters remained form the other group (group B). It is clearly revealed in the graph that members in

group B stayed only for a short time, and all diminished before the year 2010. Generally, the degree of activity of these clusters is low, as indicated by sparse co-citation lines within cluster and between clusters, no research-front terms or pivotal nodes was detected in such clusters during their existence. It can be concluded that research in these clusters is either mature or not enough attention is captured from other researchers. By the name of clusters and the contents of citing articles in them, it could be identified that these research areas cover the theme of planning, waste water and sludge treatment, integrated urban water system, land surface albedo, CO_2 capture, hydrogen production, and so forth.

Compared with the clusters in group B, those in group A are more active with close connect between each other and numerous bursting citation. From the point view of citation history, the year 1990 witnessed the start of some awareness of LCA, by a publication focused on automatic synthesis of mass-exchange networks, authored by EI-Halwagi in cluster 0 (C_A, biofuel). The research of LCA began to brisk up in the late 1990s, when LCA researches were predominated by a few publications including ISO-1997, ISO-1998 in cluster 1 (C_B, design). The first decade of the twenty-first century has shown an ever increasing attention to LCA (Guinée et al. 2011), which could be seen as a period of rapid development. Lots of highly cited publications as well as numerous bursting nodes have emerged ever since, some pivotal nodes among them are the major concern for their significant part in guiding knowledge transferring and knowledge assembling.

Starting with Keeney and Raiffa (1976), cluster 1 maintained a silent presence for the next decade until it started to liven up in 1990. Being in the active state for about 10 years, it started to diminish in 2000, soon after ISO standards for LCA were published and LCA methods moved toward harmonization. Hot discussion in cluster 1 brought out another specialty of LCAs, human health (cluster 7), which is an impact category in life cycle impact assessment phase of LCA, as indicated by dense lines between them. Cluster 7 started with Consoli et al. (1993), reinforced by Guinée (2002), and subsequently added Jolliet et al. (2003) and Rosenbaum et al.

Fig. 4 A timeline visualization of the 26 clusters (692 nodes, 2,031 links, modularity=0.8282, silhouette of each cluster>0.05). Cluster labels are automatically generated from title terms of citing articles of specific clusters
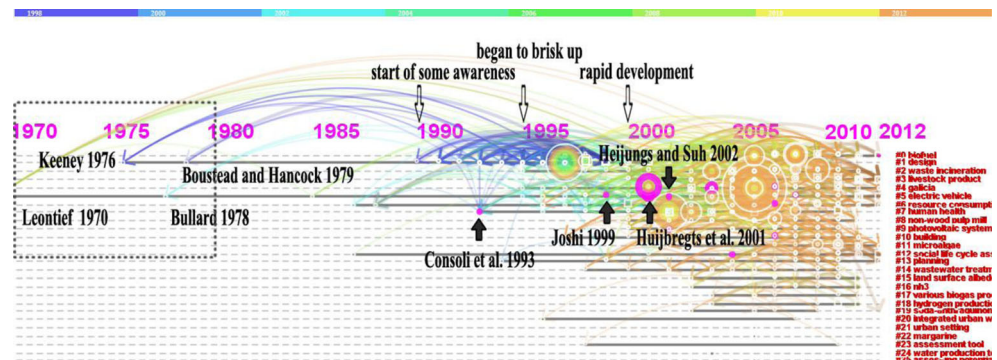
(2008). It seemed that no further study followed up Rosenbaum's work as this thread disappeared from the map in 2010.

In the year around 1970, cluster 5 (electric vehicle) originated and has continued since and it marks the maximum duration of all clusters. It has a high concentration of pivotal publications, stimulated the development of many other research fields, such as Joshi (1999) bridging to cluster 2 (waste incineration), Huijbregts et al. (2001) tying to cluster 2 and cluster 7 (human health), Heijungs and Suh (2002) linking to cluster 6 (resource consumption) and cluster 13 (planning). These three publications focused on the studies of basic LCA methodologies, which could easily lead to knowledge transferring, for example, application of LCA in different domains. Note that the citation frequency of such publications is not very high, it could be inferred that high value of publications does not always mean high citation.

4 Conclusions

LCA has been proven to be a useful focusing method to assess the environmental impact and resource depletion of products, services, and processes in order to achieve sustainable development, proven through the growing amount of literature that has been focused on it. However, there is little evidence of previous systematic, chronological, and synthesizing studies in this field. This paper tries to shed some light on this matter, configuring our main contribution as the consolidation of a large body of literature by a systematically reproducible procedure—bibliometrics—in order to present publication performance of global LCA research, characterize its intellectual structure, and trace its evolution.

Based on 7782 LCA related publications retrieved from WoS, this bibliometric study provides an overview of research in LCA by summarizing, distribution by source title, chronological, and institutional distributions. The bibliometric study especially demonstrates how co-citation analysis to do to empirically validate theoretical discussions about research fronts, intellectual base, and the evolution of research focus in LCA research domains throughout the investigation period, by using established databases combined with the use of certain bibliometric tools, i.e., CiteSpace. Because of the data source and the time frame as well as the methodologies of the study, the results present an archival view of LCA which is somewhat biased in favor of document co-citation analysis. But this study is based on the composite evaluation of thousands of cited references rather than on the evaluation of a small group of publications. Therefore, in the statistical sense, the result of this study can be seen, to a great extent, objective and fair. Nonetheless, the results have a number of implications concerning the status of LCA as a research domain.

(1) LCA-related research has increased enormously in the past 16 years, showing a pattern of exponential growth. All output of publications has been concentrated in a few journals like the *International Journal of Life Cycle Assessment*, *Journal of Cleaner Production*, *Environmental Science & Technology* as well as in some conferences proceedings. Technical University of Denmark has been the chief core institution in the field of LCA research in the past 16 years.

(2) The visual co-citation network analysis of references by CiteSpace leads us to understand thoroughly the intellectual structure of LCA research domain during the given 16-year period, via research fronts and their intellectual bases. Twenty-six specialties (clusters) of LCA research are identified. From the labels of four largest front clusters, we identified that those themes related to biofuel, process design, solid waste management, and livestock production, are the surge of interest in the LCA research domains. The active citing papers in each cluster confirm the research fronts detected by burst terms. Intellectual base of each specialty is found by analyzing those publications highly cited in corresponding cluster.

(3) Our observations provide visual insights into how LCA researches evolved during the investigated period. In the dynamic tracking analysis, many research focuses do eventually decline and perish such as planning, waste water and sludge treatment, land surface albedo, CO_2 capture, hydrogen production, etc., while some pivot publications played a role in bridging different specialty LCAs and spurred the further development of LCA research.

The main goal of this study is to provide an initial understanding of the intellectual development of LCA. It may be feasible to provide a more accurate and comprehensive picture of the intellectual structure of LCA that go beyond this study due to its bibliometric nature for future research. The future study can also give special attention to the research findings of recent or "younger" works to provide a more current picture of the field.

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