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Building life cycle assessment research: A review by bibliometric analysis

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ABSTRACT

This study aims to examine the literature related to the building life cycle assessment (LCA) that are published from 2000 to 2014 by means of bibliometric methods based on databases of the Science Citation Index and Social Science Citation Index. Of 2025 retrieved publications, 95% were journal articles. The patterns of these articles were investigated such as subject categories, journals, countries, institutions, hot topics and the most highly cited articles. The results showed a rapid growth of building LCA related publications with the USA being the leading country in terms of contributing to the largest number of articles and possessing the greatest influence. Norwegian University Science and Technology is the leading university in terms of building LCA research, which is followed by University of California at Berkeley. All the top 15 institutions possess a favorable cooperative relationship with other institutions. Most journal articles were associated with energy (521 articles), followed by material (388), sustainability (304), carbon (299) and technology with 180. According to the comprehensive analysis of the keywords, it can be concluded that subtopics such as energy, materials, environmental impacts and sustainable development will be prominent directions of future building LCA research, while life cycle costing and life cycle inventory will continue to be the common research methods. These findings help to identify hotspots in the building LCA research. Similarly, this study provides useful inputs for the decision making on the subtopic selection and publication strategy in the building LCA research.

1. Introduction

The last decades have witnessed a rapid growth of the construction industry arguably due to the social and economic development. The construction industry has significant impacts on the economy, environment and society. For instance, the construction industry is one of major consumers of resources especially the energy. Energy is the essential input during the entire life cycle of buildings not only during the operation stage but also during the manufacturing of building materials [1]. In China, buildings accounted for nearly 25% of the total primary energy consumption, and this proportion could be expanded to 35% by 2030 [2]. Particularly, with the consumption of 40% materials entering the global economy, the construction industry is responsible for 40–50% of the global output of greenhouse gases and the agents of acid rain [3].

Modern buildings are typically good-sized projects utilizing various kinds of building materials and large quantities of energy, resulting in significant influence on the environment. As a result, the last decades have witness a rapid growth of researches on the assessment of buildings across the entire life cycle. Life cycle assessment (LCA) provides a useful tool to serve this purpose by quantifying the environmental impacts and showing the practical reduction measures on assessing the sustainability performance of buildings [4–11]. Indeed, LCA has been widely employed in sustainable building related studies ([3,12,13]), especially for the energy consumption [14–16]. Some of these studies placed focuses on specific components of building [17]. This includes building materials [18], such as concrete ([19,20]), cement ([21,22]), steel [23], and wood [24,25]. Similarly, previous studies have attempted to examine the environmental impacts of the subsystems in buildings, such as heating and air conditioning systems [26], building integrated renewable energy systems ([27,28]), and electrical and thermal systems [29,30].

Therefore, it calls for a timely study to quantitatively evaluate the rapidly growing body of literature on building the LCA with the assistance of bibliometric techniques. This study aims to discover the characteristics of global building LCA literature from 2000 to 2014. Via the bibliometric method, the global trends in the building LCA research over the past 15 years are examined by analyzing the general patterns

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of publications, language, journals, subject category, country, institution, the most highly cited articles as well as hot topics. These findings provide useful inputs for the selection of subtopics in future research endeavor on the building LCA.

2. Methodology

Keywords were used to search the databases of science citation index and social science citation index in November 2014. Life cycle assessment and building were adopted as the core words. Similarly, various aspects of buildings are included such as: "building material", "building HVAC system", "building assembly" and so on. We also replaced "building" with "construction" or "architecture". As a result, 2025 publications were retrieved from databases that are published during the period of 2000–2014. Study on these documents come down to document type, annual output, author, country output, citation frequency, hot topics classification, etc.

2.1. Bibliometric methods

Bibliometric is widely recognized as a well-established research method in the information science particularly for the evaluation of research performance of academics and universities. It adopts quantitative analysis and statistical methods to analyze the quantitative relation and content information in a given field; and further examine the detailed characteristics and patterns of the featured research field. The bibliometric analysis has been used in a variety of scientific fields, such as global groundwater [31], sustainable development [32], climate change [33], solar energy and carbon market [34,35] etc.

2.2. H-index and impact factor

In this paper, h-index and impact factor are adopted as measures of influence to examine the characteristics of publication statistics on countries, journals, institutions, languages, subjects, etc.

Hirsch (h) index was introduced by Hirsch in 2005 which revolutionized scientometrics, and is considered as a quantitative method to evaluate the total effective output of a researcher with strengths of simplicity and immediate intuitive meaning [36]. According to Hirsch [36,37], h-index provides an unbiased evaluation and has a predictive value with one figure. Giving "an estimate of the importance, significance, and broad impact of a scientist's cumulative research contributions", the index can be used for authors, journals and institutions as well [36]. In this research, based on the publications related to the building LCA, h-indexes of countries and journals were calculated to evaluate their performance, respectively. The impact factor (IF) is a traditional citation metric to measure the quality and influence of journals. IF is employed in this paper to assess the relative influence of journals related to the building LCA. The impact factor of a given journal is retrieved from the 2014 Journal Citation Reports.

2.3. Content analysis

As a common form of content analysis, word frequency analysis highlights the core content of literature as the research object. This can be utilized to unearth the development trends and changes in scientific research of a given field. In order to identify the hot topics in the building LCA field more completely and precisely, synonymous keywords and congeneric phrases are merged initially and consequently grouped into categories. For example, keywords associated with energy cover "renewable energy", "embodied energy", "operating energy", "energy consumption", "energy conservation", "energy efficiency" and etc. Carbon management covers "greenhouse gas", "CO_2 emissions", "carbon footprint", "carbon tax", "carbon debt", "carbon mitigation", "global warming potential', "climate change" and etc. After initial mergence, keywords are ranked by mentioned times. Then those keywords with high occurrences are grouped into categories and listed in a table in order to further recognize hot topics in building LCA.

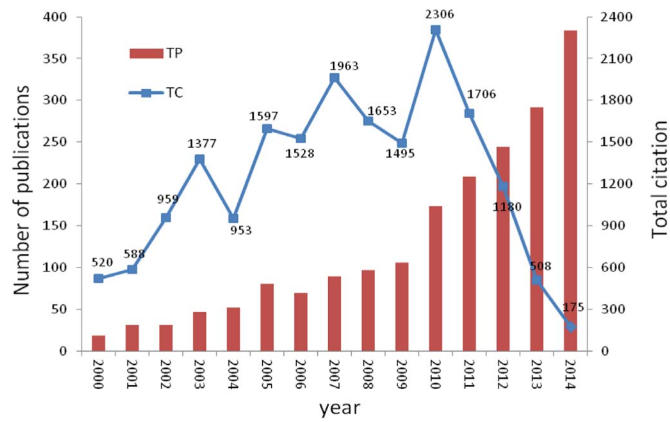

Fig. 1. TP and TC, from 2000 to 2014. Note: TP-total number of publications, TC-total citations.

3. Results

3.1. The general patterns

Of the 2025 publications retrieved from the databases, 1926 are articles followed by proceedings papers (4.64%), review (4.44%). Editorials, book chapters, software reviews and letters altogether accounted for as low as 0.52% of the total building LCA related publications. Therefore, only articles were further analyzed in this research. Articles related to the building LCA in SCI and SSCI involve 11 languages. Vast majority of these articles were written in English with 1855 records, accounting for 96.31%. This is followed by German (1.97%) and Spanish (1.14%). The other languages only occurred once or twice. This indicates that English is the predominant language in the field of building LCA research even in those non-English speaking countries such as Germany, China, Spain, and Japan.

As shown in Fig. 1, the number of publications related to the building LCA grew steadily during the past 15 years, and more rapidly since 2010. Total citation reached the peak in 2010 with a record of 2306 and then dropped gradually arguably due to the time required for the accumulated effects of new publications.

Table 1 shows the characteristics of the building LCA related publications during the period of 2000–2014. The analysis was conducted on the number of author (No. AU), the ratio of number of authors to number of publications (AU/TP), number of references (NR), and number of pages (PG). As shown in Table 1, there is a steady

Table 1
Characteristics of publication by year (2000–2014).

PY	TP	No. AU	AU/TP	NR	NR/TP	PG	PG/TP
2000	19	46	2.42	396	20.84	217	11.42
2001	31	95	3.06	574	18.52	308	9.94
2002	31	77	2.48	793	25.58	332	10.71
2003	47	136	2.89	1030	21.91	575	12.23
2004	52	176	3.38	1362	26.19	631	12.13
2005	81	246	3.04	2495	30.80	988	12.20
2006	70	213	3.04	2071	29.59	872	12.46
2007	90	288	3.20	2619	29.10	973	10.81
2008	97	303	3.12	2837	29.25	1066	10.99
2009	106	335	3.16	2930	27.64	1109	10.46
2010	173	523	3.02	5835	33.73	1919	11.09
2011	209	707	3.38	8041	38.47	2392	11.44
2012	244	811	3.32	9613	39.40	2799	11.47
2013	292	1016	3.48	11,610	39.76	3290	11.27
2014	384	1521	3.96	16,318	42.49	4242	11.05

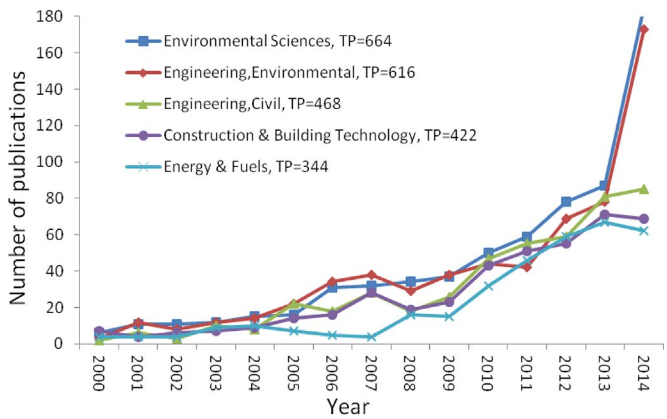

Fig. 2. Annual number of articles for top 5 subject categories (2000–2014).

growth for the number of publications per year. Similarly, the number of authors and cited references gained significant growth during the past 15 years.

3.2. Distribution of subject categories

All the 1926 articles related to the building LCA area were divided into 150 subject categories in SCI and SSCI databases. The top 5 subjects and its annual publications are demonstrated in Fig. 2. Environmental Sciences is the most popular subject with a record of 664, followed closely by Engineering, Environmental a record of 616. These top two subjects experienced a rapid growth since 2011. Ranked third and fourth respectively, Engineering, Civil and Construction & Building Technology came through a small fluctuation during 2005–2008 and increased fast since 2009. Energy & Fuels ranks the fifth and reached the peak in 2013 with a record of 282 publications.

3.3. Performance of journals

There are 512 journals that have published articles on the building LCA by 2014. Table 2 shows the distribution of these journals. Top 15 journals (in terms of TP) contributed to more than 46% of the total building LCA related publications over the past 15 years. International Journal of Life Cycle Assessment is the most influential journal with 167 publications related to the building LCA (8.67%). This is followed by Journal of Cleaner Production (134 articles) and Energy and Buildings (119). Among these journals, building and Environment ranked 4th by the number of articles, but had the highest h-index (25)

Table 2
The analysis of top 15 journals, 2000–2014.

Journal name	TP	%	IF 2014	5-year IF	h-index
International Journal of Life Cycle Assessment	167	8.70	3.089	4.297	21
Journal of Cleaner Production	134	6.98	3.59	4.088	15
Energy and Buildings	119	6.20	2.465	3.076	23
Building and Environment	110	5.73	2.7	3.022	25
Environmental Science & Technology	51	2.66	5.481	6.277	18
Building Research And Information	43	2.24	1.319	2.168	13
Journal of Industrial Ecology	41	2.14	2.713	3.146	9
Resources Conservation and Recycling	39	2.03	2.692	3.026	11
Energy	38	1.98	4.159	4.465	13
Applied Energy	37	1.93	5.261	5.597	9
Energy Policy	34	1.77	2.696	3.402	10
Waste Management	24	1.25	3.157	3.496	11
Journal of Infrastructure Systems	22	1.15	0.648	1.518	11
Wood And Fiber Science	19	0.99	0.875	0.996	11
Science of the Total Environment	18	0.94	3.163	3.906	8

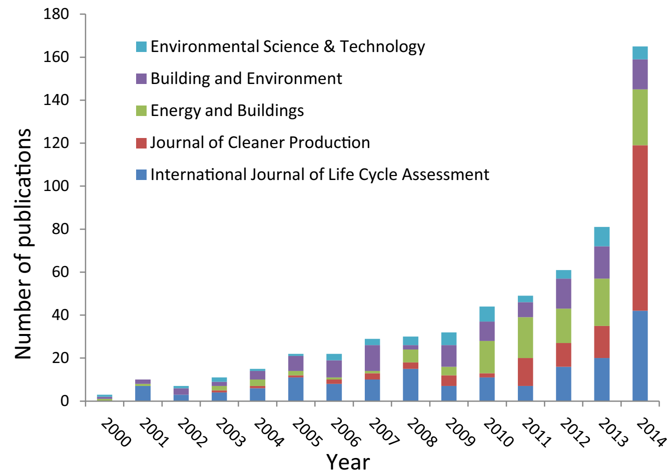

Fig. 3. Distribution of publications of building LCA across the five top journals.

among these 15 journals. This indicates that Building and Environment is one of key journals with a significant influence on the building LCA research. Fig. 3 shows the distribution of publications of building LCA across journals of the five top journals annually. As illustrated in Fig. 3, an increasing number of publications in building LCA are observed. The trend is likely to reflect the importance of LCA as an increasingly accepted approach to analyze the environmental performance of building. Journal of Cleaner Production has taken more and more shares in building LCA field as clearly shown in Fig. 3, demonstrating its increasingly important place in building LCA.

3.4. The analysis of Countries and institutions

A total of 1921 articles were analyzed for countries and research institutions as 5 articles were not provided author addresses and affiliations in SCI and SSCI databases. From 2000–2014, 89 countries have contributed to publishing articles on the building LCA. Less than 24% of these publications involved international collaboration. Fig. 4 shows the geographical distribution of case studies based on locations of building LCA studies. USA produces the most building LCA studies with 449 publications during the past 15 years, demonstrating its public interest in LCA and a specific focus on environmental optimization of building. European countries, largely driven by UK (161 publications), Spain (154), Italy (134), Germany (106), Sweden (103), Switzerland (84), are those producing the most building LCA studies, reflecting the existence in these countries of active LCA communities. A few building LCA studies have been found for Russia, a large part of South America and Africa. The shortage may be induced by the fact that studies are published in local languages that obstructs their inclusion in this study, and maybe also by the generally poor penetration of LCA in these regions.

Table 3 shows the top 10 productive countries according to a variety of indicators such as the total number of publications, the number articles involved international collaboration, etc. Six out of these top ten productive countries are from Europe, two from North America and one each from Asia and Oceania. The USA is the most productive country with the largest number in all indicators, which signals its leadership position in terms of building LCA research. It is worth noting that the proportion of articles involved international collaboration is higher than that of single country articles for all top 10 productive countries. China takes the fourth place in terms the number of total publications while gains a top three spot in terms of articles involved international collaboration. This indicated that China possesses a favorable international cooperation. However, its h-index is relatively low (17), suggesting that China had a relatively weaker influence than top three countries according to h-index: USA (36),

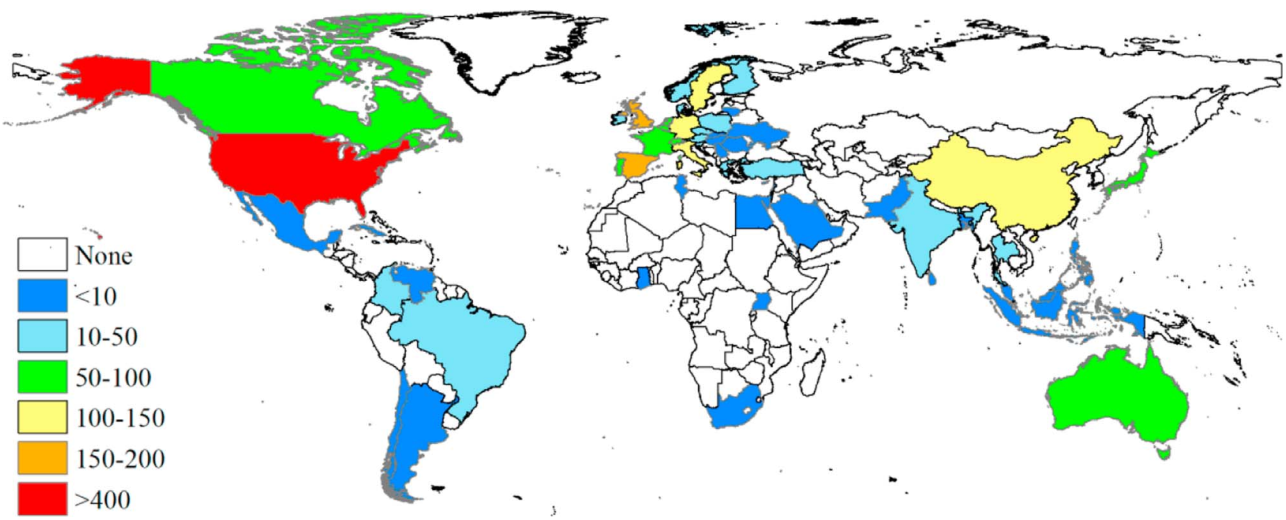

Fig. 4. Geographical distribution of publications based on locations of building LCA studies.

Table 3
Top 10 productive countries in the publications related to the building LCA during 2000–2014.

Country	TP	TP R (%)	SP R (%)	CP R (%)	FP R (%)	C%	h-index
USA	449	1 (23.5)	1 (22.22)	1 (27.93)	1 (20.2)	27	36
UK	161	2 (8.42)	3 (6.46)	3 (15.26)	3 (6.17)	40	21
Spain	154	3 (8.06)	2 (6.73)	4 (12.68)	2 (6.86)	35	20
China	137	4 (7.17)	6 (4.31)	2 (17.14)	5 (5.34)	53	17
Italy	134	5 (7.01)	4 (6.26)	7 (9.62)	4 (5.91)	31	16
Germany	106	6 (5.55)	6 (4.31)	6 (9.86)	7 (3.92)	40	16
Sweden	103	7 (5.39)	5 (4.85)	12 (7.28)	6 (4.6)	30	18
Canada	89	8 (4.66)	8 (3.64)	9(8.22)	8 (3.51)	39	20
Switzerland	84	9 (4.4)	11 (2.63)	5 (10.56)	11 (2.72)	54	16
Australia	78	10 (4.08)	9 (3.37)	13 (6.57)	9 (3.09)	36	15

Note: SP-total number of single country publications, CP-total number of publications involved international collaboration, FP- total number of publications from the first author's country.

UK (21), and Spain (20). On contrary, Canada took the third place by h-index although it ranks eighth in terms of the number of total publications and single country publications. This implies that the country with higher h-index has greater influence because of more citations.

Fig. 5 shows the annual publications related to the building LCA from top six productive countries during 2000–2014. It shows that every country gained a steady growth in annual number of publications. USA has been the leading country in terms of the annual number of publications during the past 15 years and had two substantial increases in 2005 and 2010. The remaining countries experienced a similar trend of growth in the number of publications. This indicates that the rapid development of body of literature related to the building LCA was partly driven by high-productive countries. The rapid increase of the total publications implies that much more attention has been paid to the research of building LCA in recent years in China. Italy experienced a dramatic growth in 2014 and came to the second place.

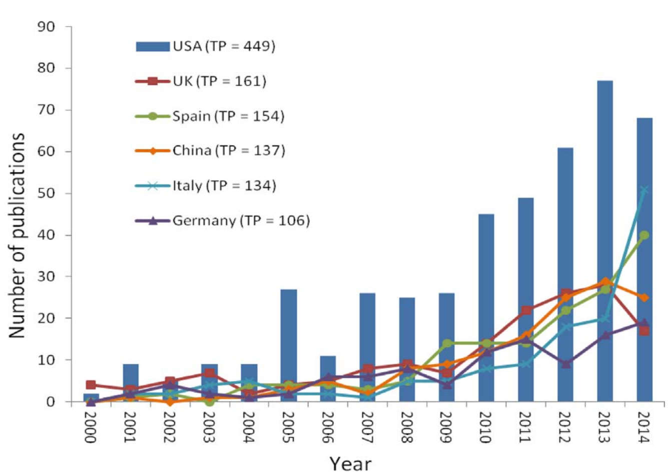

Fig. 5. Annual number of articles for the top 6 productive countries (2000–2014).

A total number of 1647 institutions contributed to the research on the building LCA in accordance with 1408 articles with the author address. More than 50% of these articles were developed by authors from multiple institutions. As shown in Table 4, among the 15 most productive research institutions, six are from the USA, three from Spain, two from Sweden, and one from Norway, Denmark, Switzerland and Netherlands respectively. Although the UK, China, Germany, Italy, Canada, France, Japan, Australia, Finland and Belgium were among the top 15 productive countries, there were no records in the top 15 productive research institutions from these countries. Norwegian University Science and Technology took the lead in total number of publications (32), followed by University of California at Berkeley (29). Nearly all these institutions possess a favorable cooperative relationship with other institutions as indicated by their high C% record (the proportion of inter-institutional collaborative publications to the total publications of each institution) except University of Zaragoza.

3.5. Main research fields of the building LCA

According to statistical analysis results, keywords of the articles retrieved from SCI and SSCI databases could be classified into "hot topics" related to building LCA. This helps to identify the common directions in a research field. Synonymous keywords and congeneric phrases listed by authors of these publications were merged in the first instance. As a result, a total number of 3986 keywords were identified. In order to locate the hot topics accurately in these 3986 keywords, the congeneric keywords are ranged together as one hot topic. For example, keywords such as environmental performance, environmental indicator, environmental cost, environmental monitoring, environmental design, environmental economics, environmental policy, and environmental standard are sorted as "environmental management". Author keywords associated with energy were mentioned in many detailed categories, such as "renewable energy", "embodied energy", "operating energy", "energy consumption", "energy conservation", "energy efficiency", etc. In this paper, these keywords are sorted into a category of "energy".

As shown in Fig. 6, with a view to the ultimate realization of

Table 4
The 15 most productive institutions, 2000–2014.

Organization	TP	TP R (%)	SP R (%)	CP R (%)	FP R (%)	C%
Norwegian Univ Sci & Technol, Norway	32	1 (1.41)	1 (1.27)	7 (1.44)	2 (0.84)	50
Univ Calif Berkeley, USA	29	2 (1.36)	2 (1.27)	9 (1.34)	1 (1.1)	52
Univ Michigan, USA	27	3 (1.25)	12 (0.74)	3 (1.75)	6 (0.73)	74
ETH, Switzerland	27	3 (1.25)	3 (1.17)	9 (1.24)	6 (0.73)	56
Tech Univ Denmark, Denmark	26	5 (1.15)	19 (0.64)	3 (1.65)	119 (0.16)	77
Chalmers Univ Technol, Sweden	26	5 (1.1)	5 (0.95)	7 (1.34)	4 (0.84)	62
Univ Rovira & Virgili, Spain	24	7 (1.04)	174 (0.11)	1 (2.37)	28 (0.42)	96
Univ Autonoma Barcelona, Spain	22	8 (0.99)	38 (0.42)	5 (1.55)	5 (0.78)	82
Univ Florida, USA	20	9 (0.99)	98 (0.21)	5 (1.55)	23 (0.47)	90
Delft Univ Technol, Netherlands	20	9 (0.94)	12 (0.64)	11 (1.24)	12 (0.68)	65
Univ Washington, USA	19	11 (0.94)	12 (0.74)	13 (1.13)	9 (0.73)	63
Univ Pittsburgh, USA	19	11 (0.94)	6 (0.95)	15 (1.03)	6 (0.73)	53
KTH Royal Inst Technol, Sweden	18	13 (0.89)	6 (0.85)	2 (1.86)	2 (0.84)	117
Arizona State Univ, USA	18	13 (0.89)	26 (0.53)	11 (1.24)	14 (0.63)	72
Univ Zaragoza, Spain	17	15 (0.84)	4 (1.06)	35 (0.72)	9 (0.73)	35

sustainability and environmentally friendly building, studies use methods such as life cycle cost, life cycle inventory, optimization and etc. to help conduct building LCA researches covering "input" aspects namely material and energy; building design, building environmental management and building technology considerations during the four stages of building life cycle; "output" as environmental impact including emission and carbon. The largest record of retrieved journal articles is in the area of energy (521 articles), followed by material (388), sustainability (304), carbon (299) and technology with 180.

3.5.1. The top five research topics

Fig. 7 demonstrates the time-trend of the top five research topics pertinent to building LCA during the past 15 years. Energy took the lead during all the 15 years with the fastest growth rate in building LCA related literature. This is followed by material, carbon and sustainability with similar amount of publications.

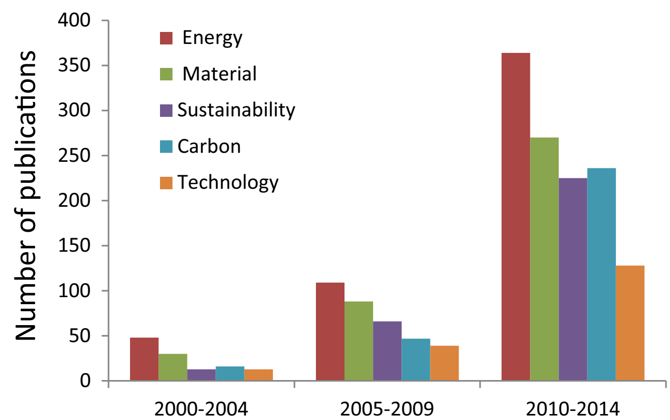

Fig. 7. The growth trend of the top five research topics (2000–2014).

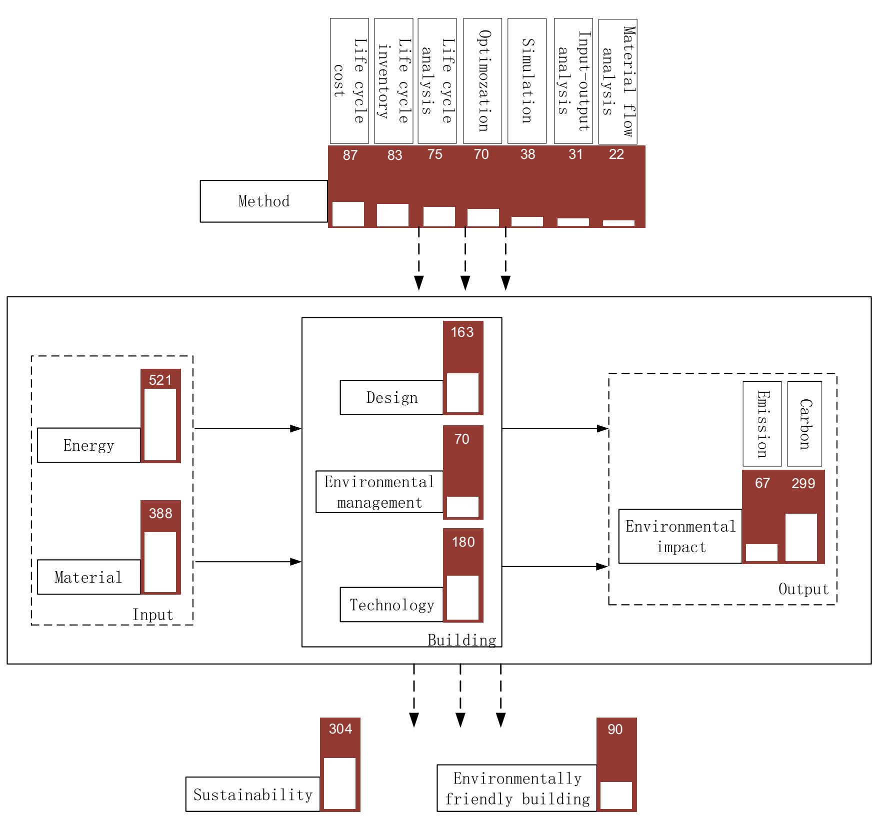

Fig. 6. Hot topics assessed in this study, expressed in number of publications.

3.5.1.1. Energy and carbon. The life cycle of a building consists of four stages, i.e. manufacture of building materials, construction, operation and demolition [3]. Amongst these stages, the building material manufacturing and operation stages have been found to be responsible for a large proportion of the environmental impacts [3,12,38]. Energy is the essential input during the whole life of building not only in the operation stage but also during the manufacturing of building materials, their transportation and assembly into buildings as well as the maintenance and demolition of buildings [3]. Energy plays a vital role in the functioning of a building, but is also impacting the environment as energy related emissions are responsible for the environmental impacts globally [3]. Undoubtedly, energy becomes the most prominent hot topic in building LCA and is worth of further discussion.

As shown in Fig. 6, energy is the largest category with 521 publications. "Energy" related keywords are "renewable energy", "operating energy", "embodied energy", "energy consumption", "energy efficiency" and "energy conservation". The long life span determines the large amount of operating energy in buildings. This includes the energy used for cooling, heating, lighting, ventilation, and equipment operation, and water supply [4]. By examining energy consumption in specific systems, the significant environmental aspects of the building during the operation stage can be defined and more practical suggestions can be provided to maximize the energy conservation. The embodied energy associated with a product covers both the manufacturing process but also the assembling process [39]. With 103 records, embodied energy is the top research topic related to "Energy". Embodied energy is difficult to measure. However, it is crucial to achieve a balance between embodied energy and operating energy over the whole life span of buildings [1]. The improvement of energy efficiency (with record of 48) and substitution primary energy (with record of 24) with renewable energy (35) will help to achieve to the carbon emission reduction.

Carbon and energy are closely related. A lot of attention has been paid to CO_2 emissions in the life cycle of buildings. Keywords related to carbon are common in these literatures covering greenhouse gas, CO_2 emissions, carbon footprint, carbon tax, carbon debt, carbon mitigation, global warming potential, climate change, etc. These keywords have been one of main focuses of building LCA related literature over the last 15 years, taking the third place with 299 articles (8.67%).

3.5.1.2. Material. In terms of volume used, the major construction materials include sand, cement, concrete, timber, brick, and steel [40]. It is well recognized that there are significant impacts of energy consumption on the environment. The total number of publications with keywords related to material is 388 including specific materials mentioned as concrete, wood, steel and cement during the last 15 years. Fig. 8 shows the rise of four main building materials during the past 15 years. As shown in Fig. 8, concrete experienced a dramatically increase with the publications surging from 1 to 66 during the period of this study.

Building materials are closely related to the embodied energy of buildings, which includes the energy consumed in manufacturing of building materials. For buildings with concrete structure, it is feasible to achieve the embodied energy reduction by using recycling and novel materials, as well as through the more efficient use of materials resulting from optimized structural designs. Alternatively, efforts can be made to reduce the concrete volume by using more high-strength concrete. The CO_2 emissions per cubic meter of high strength concrete are higher than that of general strength concrete. However, less amount of concrete is required for the same structural element [41]. Coupled with the longer life span, the life cycle CO_2 emission of high strength concrete buildings is notable lower than that of general strength concrete buildings [42]. Similarly, an optimum material solution would have the indispensable structural properties of concrete but with lower thermal conductivity, which can provide a better thermal insulation system that consumes less energy for cooling and heating at the operation stage, and therefore reduce the GHG emissions [43].

3.5.1.3. Sustainability. "Sustainability" and "environmentally friendly building" emerged as hot topics with 304 and 90 publications respectively. Sustainable construction was defined by Professor C.J. Kibert in 1994 at the 1st International Conference on Sustainable Construction as "the creation and responsible maintenance of a healthy environment, based on resource efficient and ecology principles" [44]. In essence, sustainable building should take a triple bottom line approach where economic, social and environmental aspects should be taken into consideration during the entire life cycle of buildings [45]. The accomplishment of a high-performance, low-environmental-impact sustainable buildings can be fulfilled from many aspects including sustainable materials, sustainable operations, sustainable services, and sustainable consumption meaning to incorporate sustainability principles into every part of a building.

3.5.1.4. Technology. Technology is an important tool to achieve sustainable building. As shown in Fig. 9, thermal technology took the lead in terms of growth trend of main technologies with a total of 62 publications. Thermal insulation is one of most important methods to reduce the energy consumption in buildings [46]. Appropriate thermal insulation application in buildings helps to cut down energy consumption leading to a favorable result of fossil fuel saving as well as other advantages such as eliminating the problems of condensation

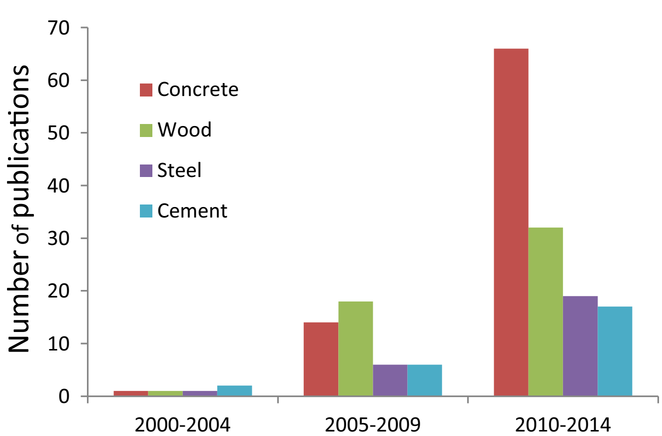

Fig. 8. The growth keywords trend of main building materials (2000–2014).

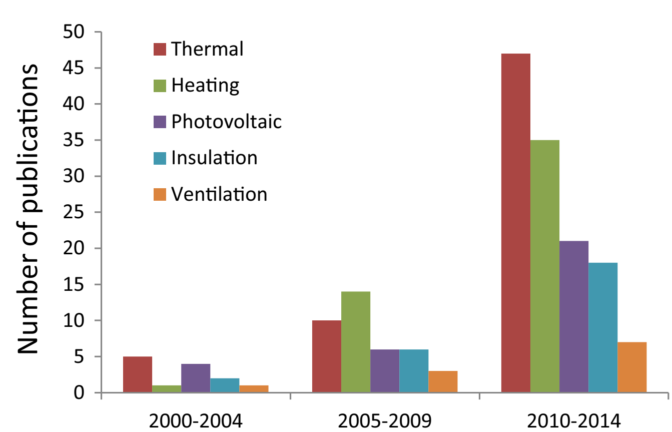

Fig. 9. The growth trend of main technologies (2000–2014).

and mold formation on interior surfaces of the walls [47]. Further, based on the selection of proper insulation material, as well as the resolution of optimal insulation thickness, the optimum point exists to minimize the energy consumption over the whole life time and to maintain a minimum investment for insulation at the same time.

3.5.2. Research method

In the research field of building LCA, assistant number of research methods have been used, such as life cycle costing (87 publications), life cycle inventory (83 publications), life cycle analysis (75 publications), optimization (70 publications) and etc.

There are various types of costs associated with a building across its lifecycle stages, i.e. manufacture of building materials, construction, operation and demolition. In the life cycle costing approach, all relevant present and future costs associated with the system are calculated in terms of the present value [48]. Life cycle cost (LCC) may be used to determine how to reduce the cost of ownership or to compare alternative investments in whole buildings or building elements. It is a useful decision-making tool when comparing options that have different initial costs as well as implications for subsequent operational cost [49]. To facilitate comparison, the alternatives need to provide the same outcome or level of service. In a study of costs and energy use [50] used life cycle costing approach to compare 4 options, i.e. renovate existing property, buy another property and renovate, buy land and build or do nothing. Their study revealed that "buy and build" was only marginally more expensive than the "do nothing" option with the lower operational energy costs almost outweighing the difference in capital cost. A growing number of studies on building LCA are applying the life cycle costing approach to identify an optimal scheme for both good quality and function with the lowest overall cost (see Fig. 10).

Optimization became very prominent in the recent studies (2010–2014), and this method has been employed in a number of areas such as: structural design, life cycle cost, total weight of materials, energy conservations and so on in building LCA [51–57]. Individual optimization analysis should be undertaken with each building due to its uniqueness.

3.5.3. Other hot topics

"Environmentally friendly building" is another hot topic with 90 publications which contains "green building", "low-energy building", "low-carbon building", "zero-emission building" and "ecological sustainable building". These environmentally friendly buildings respond to the call of sustainable development in buildings and help to mitigate the various environmental impacts to a certain degree. Indeed, there is a growing uptake of green buildings worldwide. There are four key aspects of green buildings, i.e. the indoor environmental quality; the whole life cycle of buildings; feasibility of green building technologies; and comprehensive utilization of renewable energy resources.

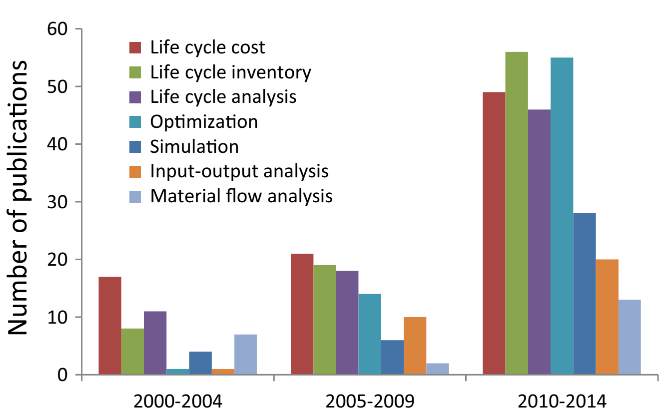

Fig. 10. The growth trend of main research methods (2000–2014).

"Environmentally friendly building" is an inevitable trend in the fast developing society to maintain the environment quality.

Similarly, "Design" is a hot topic in the research field of building LCA with 163 publications in SCI and SSCI databases. It is imperative to perform a proper design and take into consideration more practical technologies at the very beginning of a building project.

The construction industry has significant impacts on the social and economic development in global scales which consume a large quantity of energy and other natural resources [3], partly because of its long life span. To figure out what impacts a building has brought into the environment, the research on life cycle assessment of a building has been carried out. Apart from carbon emissions to the air, there are various pollutants emitting to the environment which results in serious environmental issues such as ODP (ozone depletion potential), AP (acidification potential), and EP (eutrophication potential). These associated keywords are all classified as "emission" in hot topics and gained corresponding concern in publications related to building LCA.

3.6. The most highly cited articles

Table 5 shows the most highly cited articles each year during 2000–2014, including the total citation times, average annual citation times, article's name, journal's name and the country of the first author. The impact of publications can be evaluated by means of variations to the number of citations every year [33]. As shown in Table 5, the authors of four articles are from USA, two from Canada and the rest countries appear only once.

Among the building LCA related articles, the most frequently cited article is "Energy use in the life cycle of conventional and low-energy buildings: A review article" [58]. This article was published in Energy and Buildings and had been cited 217 times with the highest annual citations (27). A literature survey was conducted in that paper on buildings' life cycle energy use leading to a total of 60 cases from nine countries. That paper revealed that design of low-energy buildings achieved the reduction of the life cycle energy demand with different design criteria. The second most highly cited article is "A low energy building in a life cycle - its embodied energy, energy need for operation and recycling potential" [59]. It was published in Building and Environment in 2002 with 179 citations. That paper presents embodied energy accounted for 45% of the total energy required in a life span of 50 years of a building and the recycling potential was between 35% and 40% of the embodied energy. The third highly cited article is "Life cycle energy and environmental performance of a new university building: modeling challenges and design implications" [60] and published in Energy and Buildings in 2003. That paper used computer modeling methods to determine the primary energy consumption for different systems and recognized all impact categories measured correlate closely with primary energy demand. Similarly, a life cycle model was developed in that study to assist decisions for the building design.

Major progress has been achieved in energy, material and environment impacts during the time period of 2000–2014. Many publications related to these fields are listed in Table 5 as the most frequently cited articles. It is worth noting that articles involving environmentally friendly building is among the most highly cited articles in 2005 and 2010, entitled as "Applying multi-objective genetic algorithms in green building design optimization" (2005) and "From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB)" (2010).

4. Conclusions

Via the bibliometric methods, 2025 publications related to building LCA were retrieved SCI and SSCI databases (2000–2014) and 95.11% of them were journal articles. The analysis reveals that the articles on building LCA have gained a rapid growth over the past 15 years. A total

Table 5
The most cited articles related to building LCA each year during 2000–2014.

Year	TC-2014	TC/Y	Article	Journal	Country
2000	85	6	Life-cycle energy analysis of buildings: a case study	Building Research and Information	Australia
2001	80	6	Analysis of embodied energy use in the residential building of Hong Kong	Energy	China
2002	179	14	A low energy building in a life cycle - its embodied energy, energy need for operation and recycling potential	Building and Environment	Sweden
2003	170	14	Life cycle energy and environmental performance of a new university building: modeling challenges and design implications	Energy and Buildings	USA
2004	64	6	Construction materials and the environment	Annual Review of Environment and Resources	USA
2005	120	12	Applying multi-objective genetic algorithms in green building design optimization	Building and Environment	Canada
2006	114	13	Comparing high and low residential density: Life-cycle analysis of energy use and greenhouse gas emissions	Journal of Urban Planning and Development	Canada
2007	217	27	Energy use in the life cycle of conventional and low-energy buildings: A review article	Energy and Buildings	Norway
2008	67	10	A life-cycle energy analysis of building materials in the Negev desert	Energy and Buildings	Israel
2009	140	23	Sustainability in the construction industry: A review of recent developments based on LCA	Construction and Building Materials	Colombia
2010	79	16	From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB)	Energy and Buildings	Ireland
2011	67	17	Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential	Building and Environment	Spain
2012	33	11	Design of low-emission and energy-efficient residential buildings using a multi-objective optimization algorithm	Building and Environment	USA
2013	20	10	Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts	Building and Environment	USA
2014	10	10	Wood as a building material in the light of environmental assessment of full life cycle of four buildings	Construction and Building Materials	Poland

number of 512 journals have published the building LCA related articles that are classified into the 150 subject categories. Five most influential journals were identified, i.e. International Journal of Life Cycle Assessment, Journal of Cleaner Production, Energy and Buildings, Building and Environment, and Environmental Science & Technology, contributing more than 30% to the total publications on the building LCA. Environmental Sciences is the most popular subject with a record of 664. A high frequency of “environmental management” indicates the current emphasis on the environmental problems in the building LCA research.

The USA is the most productive country with the largest number in all indicators, indicating its leadership position in the building LCA research. China took the fourth place with a relatively higher number of publications involved international collaboration however with a comparatively lower h-index. Norwegian University Science and Technology is the most productive institution followed by University of California at Berkeley. All the top 15 institutions possess a favorable cooperative relationship with other institutions.

The most frequently covered hot topics in the research field of the building LCA are mainly related to energy, materials, carbon, sustainability and life cycle cost. As for research methods, an integrated approach between the LCA and LCC has attracted an increasingly level of attention from researchers.

Bibliometric technique evaluates and quantifies the patterns of publications addressing a particular subject and examines publication characteristics such as authorships, citations, and impact factor. Bibliometric technique offers a quantitative perspective to provide a better understanding of characteristics associated with global building LCA researches. Both hot topics and popular research methods were identified. This offers a useful reference to researchers to choose the specific field of building LCA to study and associated research methods. Moreover, this study revealed the most productive institutions in terms of building LCA research. This could encourage the international collaboration with these institutions in future endeavors.

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