A REVIEW OF LIFE CYCLE RESEARCH OF THE BUILT ENVIRONMENT AT DIFFERENCE SCALES: A CITATION ANALYSIS USING BIG DATA

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ABSTRACT

Life cycle assessment has been used as an analysis tool to help decision-makers plan for mass urbanization and building construction; however, the research to date focuses on either the individual building scale or overall urban scale. Although several methodologies have been applied to both scales, the results have not been reconciled or synchronized. In light of this, this paper first presents a systematic literature review using bibliometric network data to assess state-of-the-art knowledge of the use of LCA at different scales from 1990–2017. Second, the paper identifies the main research foci at the building and urban scales. At the building scale, three research focal points are identified: building materials and products, design solutions, and energy consumption/emissions reduction. At the urban scale, there are three research areas of focus as well: urbanization and infrastructure planning, urban metabolism (water/energy/waste synergy), and complexity of urban issues. Next, the most influential papers and journals are presented. Drawing upon the findings from the literature review, major gaps in current research activities are identified as the building-centric approach, energy performance–centric approach, and lack of consideration for uncertainties. These are critical areas requiring further study and research.

KEYWORDS

life cycle assessment, bibliometric network data, building

1. INTRODUCTION

Addressing the ecological impacts of the built environment requires an understanding of global trends in the building sector. In 2011, the world's urban population represented 52.1% of the total population and forecasts predict an increase to 58% and 67.2% by 2025 and 2050, respectively (Anderson et al. 201%). This projected mass migration to urban areas illustrates the increasing importance of the built environment's total impact on ecosystems. Life cycle assessment has been used as an analysis tool to help decision-makers plan for mass urbanization and building construction; however, the research to date focuses on either the individual building scale or overall urban scale. Although several methodologies have been applied to both scales, the results have not been reconciled or synchronized. Many studies have centered on quantifying

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environmental impacts at the building scale (Utama et al. 2009, Treloar et al. 2000, Fay et al. 2000, Utama et al. 2008, Suzuki and Oka 1998, Cole and Kernan 1996, Adalverth 1997, Reddy et al. 2003, Thormark 2002, Li et al. 2011, Wang et al. 2005, Bribian et al. 2009), and robust methodologies have been established and developed. At the urban scale, certain methods have been implemented and tested to quantify the ecological impact of large built environments that include multiple buildings (Stephan et al. 2013, Kennedy et al. 2011, Davila and Reinhart 2013). However, assessments of environmental impacts of buildings and urbanization have been largely confined within their own singular scales. An overview of research activities, foci, and trends is the first step to creating an integrated framework to understand the environmental impacts of the built environment. A review of cutting-edge knowledge in the life cycle assessment (LCA) approach and studies on the built environment is meant to (1) identify the main research areas within each scale, (2) gain insight into the size of the different research focal points, and (3) identify any research gaps. The analysis results are visualized and explained in sections 3 and 4. Then, current research gaps and future needs are outlined in section 5. The conclusion is drawn in section 6, upon an analysis of sections 2 through 5.

2. RESEARCH MATERIALS, METHODS, AND TOOLS

The research methodology is comprised of *quantitative* and *qualitative* components.

Quantitative Research

Citation analysis, co-citation analysis, and text mining are used for quantitative studies. **Citation analysis** (**CA**) is the bibliometric method used to quantitatively evaluate scientific and academic literature to assess the quality of an article or the impact of study/research projects, authors, journals, or institutions. **Co-citation analysis** (**CCA**) is a bibliometric method used to measure the correlations among a variety of academic papers based on the rationale that shared references suggest an intellectual connection. CCA is a form of document coupling that measures the number of documents that have cited a given pair of documents (Small 2973); it is used in this research to trace origins and fields related to life cycle assessment studies in the built environment. **Text data mining** (**TM**) is the process of deriving high-quality information from text-based documents (e.g., titles, keywords, and abstracts) to identify patterns and trends. Automated content analysis for text—which draws on techniques developed in natural language processing, information retrieval, and text mining—has boomed over the past several years in the social sciences and humanities fields (O'Connor et al. 2011, Zhai and Massung 2016) but is rarely used in engineering fields.

Bibliometric research is a research technique for studying science-based citation data, which originated in the early twentieth century. CA and CCA are very well-established branches of bibliometric research that are used to evaluate the relative importance or impact of an author, article, or journal. Since citation frequency reflects a journal or article's value, citation analysis can be conducted to establish the impact of a particular study and identify the research focus and pattern, based on citation patterns (Garfield 1972, Narin 1976, Moed 2006, Harzing et al. 2008, DeBellis 2009). Applying mathematical and statistical models in CA and CCA are primary techniques that are used to date. Rapid changes in digital technology have introduced new techniques and methods that are used in bibliometric research to capture large amounts of text data available online. For example, TM is a fast-developing technique that extracts critical information from unstructured datasets—unlike citation. TM techniques involve information retrieval, text analysis, information extraction, clustering, visualization, machine learning, and data mining (Tajman and Vesely 2005, Nagarkar et al. 2015). TM is particularly viable in a multidisciplinary research where co-citation patterns appear to be difficult to decipher. Integrating TM in citation and co-citation analysis helps researchers to process unstructured information, such as abstracts from a thousand papers, in the matter of a couple seconds and extract the meaningful numeric indices from the text, eventually feeding them into statistical and machine learning algorithms. Using machine-learning algorithms, the information derived from a large text dataset could be used to form meaningful and rational summaries or conclusions based on the words contained. This method/technique could be used on clusters of words or to determine the relationship between words. Put simply, text mining turns words into numbers that can be computed and analyzed.

To analyze and interpret the results from CA, CCA, and TM, maps are often constructed to help visualize the data. Two types of maps can be distinguished that are commonly used in bibliometric research: distance-based and graph-based maps (Van Eck et al. 2010, Garfield 2009). In a distance map, the distance between two items generally indicate the relation and correlation. For representing literature review results, the closeness between two research topics could be viewed as a representation of the intellectual connection of the research topics or areas. Graph-based maps indicate the distance between two items but do not need to reflect the strength of the relation between the items (Van Eck and Waltman 2009). The relation between items are represented by lines. There are a variety of mapping techniques used in bibliometric research, such as multidimensional scaling (Stephan et al. 2013), Van Eck's VOS mapping techniques (Van Eck et al. 2010, Berkes and Folke 1998), VXIrd, Pajek (Davila and Reinhart 2013), and Gephi. The most commonly used technique is multidimensional scaling.

For this project, VOSViewer was chosen for its two-dimensional distance-based map (Moed 2006). VOS stands for "visualization of similarities" and aims to locate words in a low-dimensional space in such a way that the distance between two words reflects the similarity or relatedness of the words as accurately as possible (Van Eck et al. 2010). VOSviewer constructs a map based on a co-occurrence matrix and consists of three steps. *The first step* is to obtain a similarity matrix; in *the second step*, a map is constructed by applying the VOS mapping technique to the similarity matrix; then, in *the final step*, the map is translated and reflected. The similarity or association strength between different words measured in VOSviewer depends on the total number of co-occurrences of words together and the number of occurrences of the terms separately. In a VOS-constructed map, different cluster maps represent different research foci; the sizes of the nodes indicate the relevance of the items—including research topics, authors, sources, or countries—and the distance between nodes illustrates the intellectual connections.

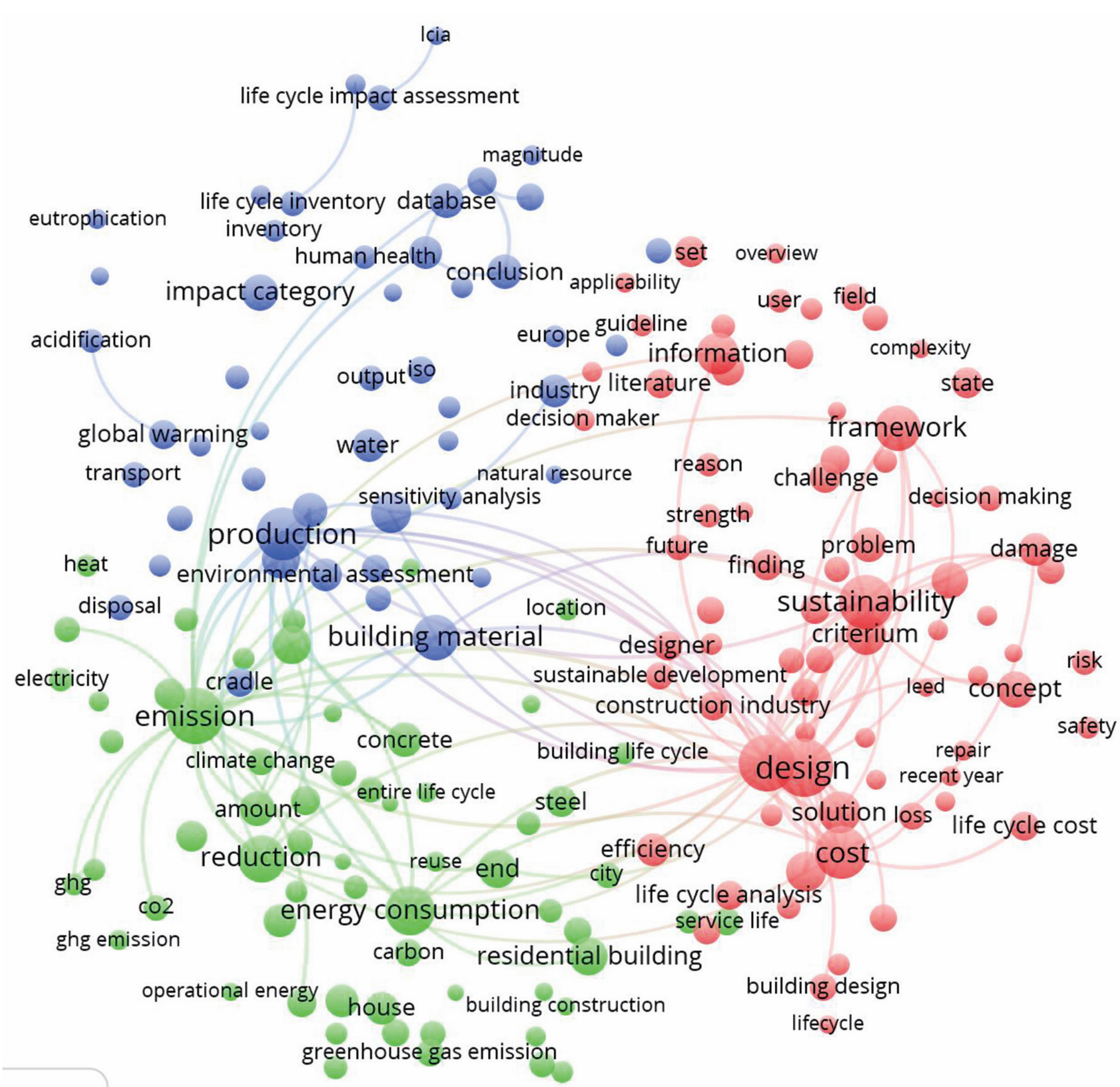
Qualitative Research

After creating an overview of research activities based on the map constructed with VOSviewer, the author identified the most active research areas, trending terms, and influential papers. Then, a qualitative review of all studies was conducted to reduce the article to a total of 52 studies that were applicable to the scope of this study. A focused review was carried out on the 15 most influential papers in each scale, as a means of drawing findings and identifying research gaps and needs. Sections 3 and 4 highlight and discuss the main results from the LCA at the building and urban scales, respectively. Two tabular summaries of the main results of the most influential papers are given in Tables 1 and 2 as well.

3. EXISTING RESEARCH ON LIFE CYCLE ASSESSMENT – BUILDING SCALE

A VOSviewer map was used to determine influential studies, thinkers, and concentrated research topics and their correlations. In order to identify the research areas of focus, a term map was created based on a corpus of scientific publications. The corpus of scientific publications includes 1,063 articles found in Web of Science (WOB) from 1990–2017 using the key search words, "life cycle assessment," "life cycle analysis," "buildings," and "architecture." The co-occurrence frequencies of terms (text) were determined based on a minimum of 20 occurrences of a term, and out of the 22,459 terms, 315 meet the threshold. For each of the 315 terms, a relevance score was then calculated. Based on this score, the most relevant terms were selected, with the default choice in the program being to select 60% of the most relevant terms. Altogether, 189 terms were selected for LCA research at the building scale, with the results shown in Figure 1. Based on VOSviewer clustering techniques, the terms in the dataset were divided into three

FIGURE 1. Term map representing the main research areas of LCA at the building scale.



clusters, with the colors indicating the different research clusters and the adjacency of nodes from different clusters suggesting the intellectual connection of different fields.

- Cluster 1 (blue): building materials, products, environmental assessment, impacts (left)
- Cluster 2 (red): design solutions/costs, sustainability/criteria, framework (right)
- Cluster 3 (green): energy consumption, emissions, reductions (lower)

These clusters represent three major research focal points: ***building materials and products***, ***design solutions***, and ***energy consumption and emissions***. Section 3.1 explains each of the areas of focus in detail.

3.1 Three Research Focal Points

Building Materials and Products

The majority of building materials studied in academic publications concentrate on conventional materials used for base building, such as concrete and steel framing. Concrete and steel account for 20–35% and around 12–22%, respectively. Together, steel reinforcement bars and concrete account for 50–80% of the environmental impact from buildings. Consequently, one of the basic ingredients of concrete—cement—has been studied extensively. It accounts for 4–5% of overall CO_2 emissions from the building industry (Chau et al. 2007, Guggemos and Horvath 2005, Bribián et al. 2011, Wu et al. 2005). Other common building materials that have been researched are brick and wood (Tettey et al. 2014). Koroneos and Dompros (2007) used data provided by a local brick manufacturer, together with published references, to study the brick production process and identify possible areas for improvement in brick production. Additionally, Ximens and Grant (2012) quantified the greenhouse benefits of wood products and found that replacing all floors and sub-floors with timber could reduce greenhouse gas emissions from buildings. Jönsson et al. (1997) studied different kinds of floor materials—including wood, vinyl, and linoleum—and concluded that solid wood appeared to be the most environmentally preferable material. Other less common building materials that have been studied include ceramic, marble, and different types of stone. The most commonly used building materials have not changed for decades, and, following 2014, there has not been much grounding-breaking LCA research about building materials. The only new, advanced material to become a research focus in the past three to five years has been nano-materials—phase-change materials and their application as paint, coating, and building envelope materials (Babaizadeh and Hassan 2013, De Gracia et al. 2010, Tettey at al. 2014, Kim et al. 2016).

Design Solution

The second area of focus is architectural design, which includes location, orientation, building façade design (glazing ratio), building density and massing, and related sustainability criteria. The building location and orientation will have a considerable impact on energy consumption and, therefore, on the overall environmental impact (Khasreen et al. 2009). Yohanis and Norton discovered the critical glazing-to-wall ratio of 55% by using a generic office building located in the United Kingdom (Yohanis and Norton 2002). Pacheco and team members studied different design factors—such as building compact factors, orientation and shape, and building envelope—and concluded that the factors with the greatest repercussion on the final energy demand were building orientation, shape, and the ratio of the external building surface to the building volume (Pacheco and Martínez 2012). Building orientation and shape are major design decisions made in the early design stage that cannot be reverted; therefore, integrating the concept of LCA in the early design stage will help the design team to find an optimized solution for building performance while minimizing the environmental impact. Even with active research in this area, the knowledge translation has been slow. While there are several quite robust design codes for building mechanical system optimization (occurs in a later design stage), such as the ASHRAR standard, there is a lack of systematic design guidelines focused on architectural design optimization. Consequently, the opportunity to translate the research findings into practical design solutions is tremendous.

Energy Consumption and Emission Reductions

The third research focus is energy consumption and emissions reductions. This area is expected to produce results since energy consumption has a direct correlation with emissions reductions, and it is the only overlapping research focus in both the building and urban scales. This research focal point examined the construction process, operation phase, and building material-acquiring phase, and results reveal that the energy consumed during the construction phase accounts for a very small percentage and, therefore, has little environmental impact on the entire building life cycle. The main influential phase is the building operating phase, and the largest environmental impact, CO_2 emissions, is associated with the operating energy (Flower and Sanjayan 2007, Norman et al. 2006, Fuller and Crawford 2011, Jiao et al. 2011, Jones and Kammen 2014, Glaeser and Kahn 2008). For example, a study conducted on three single-unit dwellings showed that the greatest environmental impact occurred during the operational stage, accounting for about 70–90% of the whole life cycle impact (Wiedenhofer et al. 2013). The second most important consumption category is embodied energy. Venkatrama Reddy and Jagadish estimated the embodied energy of a residential building consisting of different low-energy materials and obtained a 30–45% reduction in embodied energy (Jones and Kammen 2014). Furthermore, Thormark studied 90 case projects of residential buildings and found that the share of embodied energy in low-energy buildings could reach up to 57%—or even 83%—when renewable energy sources were used for electricity production (Glaeser and Kahn 2008).

3.2 Most Influential Papers and Journals

Table 1 presents the most influential (cited) paper for each year, during the years 1990–2017, including the total citation time (TC–2017), average citation times per year (TC/Y), paper title, journal name, and first author information. The impact of publications can be evaluated by means of variations to the number of citations every year [40]. Table 1 illustrates the most influential journal as being the *Journal of Building and Environment*, with seven papers among the top 15 most citied articles (50%); followed by *Building Research and Information*, with three papers; and the *International Journal of Life Cycle Assessment*, with two papers. The most cited article was "Applying multi-objective genetic algorithms in green building design optimization" (Wiedenhofer et al. 2013). This paper was published in *Building and Environment* and has been cited 209 times since 2005, with a 16.08-per-year citation rate. In this publication, life cycle analysis methodology is employed to evaluate design alternatives for both economic and environmental criteria (Chester and Horvath 2009), such as building orientation and wall-to-window ratio, among others. In addition, life cycle environmental impacts were evaluated, and the authors presented a multi-objective optimization model that could assist in a green building design (Chester and Horvath 2009). The second most cited article was "Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification," also published in *Building and Environment*, with a total of 155 citations since 2009. This paper presented cutting-edge research regarding the application of LCA in the building sector, providing a list of existing tools, drivers and barriers, potential users, and purposes of LCA studies in this sector. The analysis results revealed that embodied energy can represent more than 30% of the primary energy requirement during the life span of a single house. Furthermore, the energy certification processes implemented by European countries are the direct consequences of Direct 2002/91/EC. Integrating the life cycle in the energy certification process allows for the promotion of sustainable buildings with low energy consumption and high efficiency and innovation in the construction sector (Chester and Horvath 2012). The third most influential study was "Greenhouse gas emissions due to concrete manufacture," published in the *International Journal of Life Cycle Assessment*, with 155 citations since 2007. This research project aimed to quantify the CO_2 emissions associated with the manufacturing and placement of concrete and found Portland cement to be the primary source of CO_2 emissions generated by typical commercially produced concrete mix. The top three most referenced papers cover all three research focal points: design/sustainability, materials/products, and energy/emissions reductions. Major research progress has been achieved in these three top research areas during the period of 1990–2017. Fifteen publications related to these areas of focus are listed in Table 1 as the most influential studies. In particular, the study by Wang et al., aimed at assisting designers to produce better design solutions, is the most cited study, as a growing number of practitioners and researchers have realized that most critical and influential decisions having a considerable effect on the reduction of building energy consumption, and environment and human health impacts are typically determined during the early design stage. Therefore, providing the design team with adequate and accessible information plays an important role in building a more sustainable future. Furthermore, disseminating this information and knowledge is essential to society's future success.

4. EXISTING RESEARCH ON LIFE CYCLE ASSESSMENT – URBAN SCALE

The process used in section 3.0 was repeated to identify research focal points of LCA at the urban scale. The corpus of scientific publications that included the 340 articles from WOS was used to create a term map, with the keywords used in the search being "life cycle assessment," life cycle analysis," "urban," "city," and "district." The size of research activities at the urban scale is substantially smaller than those at the building scale; therefore, less occurrence frequency was used to create the term map. The co-occurrence frequencies of terms (text) were determined based on a minimum of 10 occurrences of a term. At the end, 296 out of 13,218 terms met the threshold. For each of the 296 terms, a relevance score was then calculated. Based on this score, the most relevant terms were selected, with the default choice in the program being to select 60% of the most relevant terms. Altogether, 178 terms were selected for LCA studies at the urban scale, with the results shown in Figure 2. Four clusters of terms are illustrated in Figure 2.

- Cluster 1 (blue): problems, urbanization/planning, challenges/changes (left)
- Cluster 2 (red): building, information, framework (upper)
- Cluster 3 (green): waste, global warming, impact category (right)
- Cluster 4 (yellow): infrastructure, water/treatment, greenhouse gas emissions (middle)

Cluster 4 is interwoven with clusters 1 and 3; in the term map, the closeness of the terms represents the intellectual connection and shared research interests and trends. Therefore, the

TABLE 1. The most cited articles related to LCA at the building scale, each year during 1990–2017.

Year	TC-2017	TC/Y	Paper Title	Journal	Author	Topics	Country
2005	209	16.08	Applying multi-objective genetic algorithms in green building design optimization	*Building and Environment*	Wang et al.	Design/ sustainability	Canada
2009	155	17.22	Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification	*Building and Environment*	Zabalza Bribian et al.	Energy/ emissions	Spain
2007	155	14.09	Greenhouse gas emissions due to concrete manufacture	*International Journal of Life Cycle Assessment*	Flower et al.	Materials/ products	Australia
2011	153	21.86	Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential	*Building and Environment*	Zabalza Bribian et al.	Materials/ products	Spain
2000	138	7.67	Life-cycle energy analysis of buildings: a case study	*Building Research and Information*	Fay et al.	Energy/ emissions	Australia
2009	131	14.56	Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy	*Building and Environment*	Blengini	Materials/ products	Italy
2007	127	11.55	Key elements in a framework for land use impact assessment within LCA	*International Journal of Life Cycle Assessment*	Canals et al.	Design/ sustainability	UK
2006	127	10.58	Life-Cycle Assessment of Office Buildings in Europe and the United States	*Journal of Infrastructure Systems*	Junnila et al.	Materials/ products Energy	Finland/ US
2006	109	9.08	Assessment of the decrease of CO2 emissions in the construction field through the selection of materials: Practical case study of three houses of low environmental impact	*Building and Environment*	Gonzalez et al.	Materials/ emissions	Spain

TABLE 1. *(Continued)*

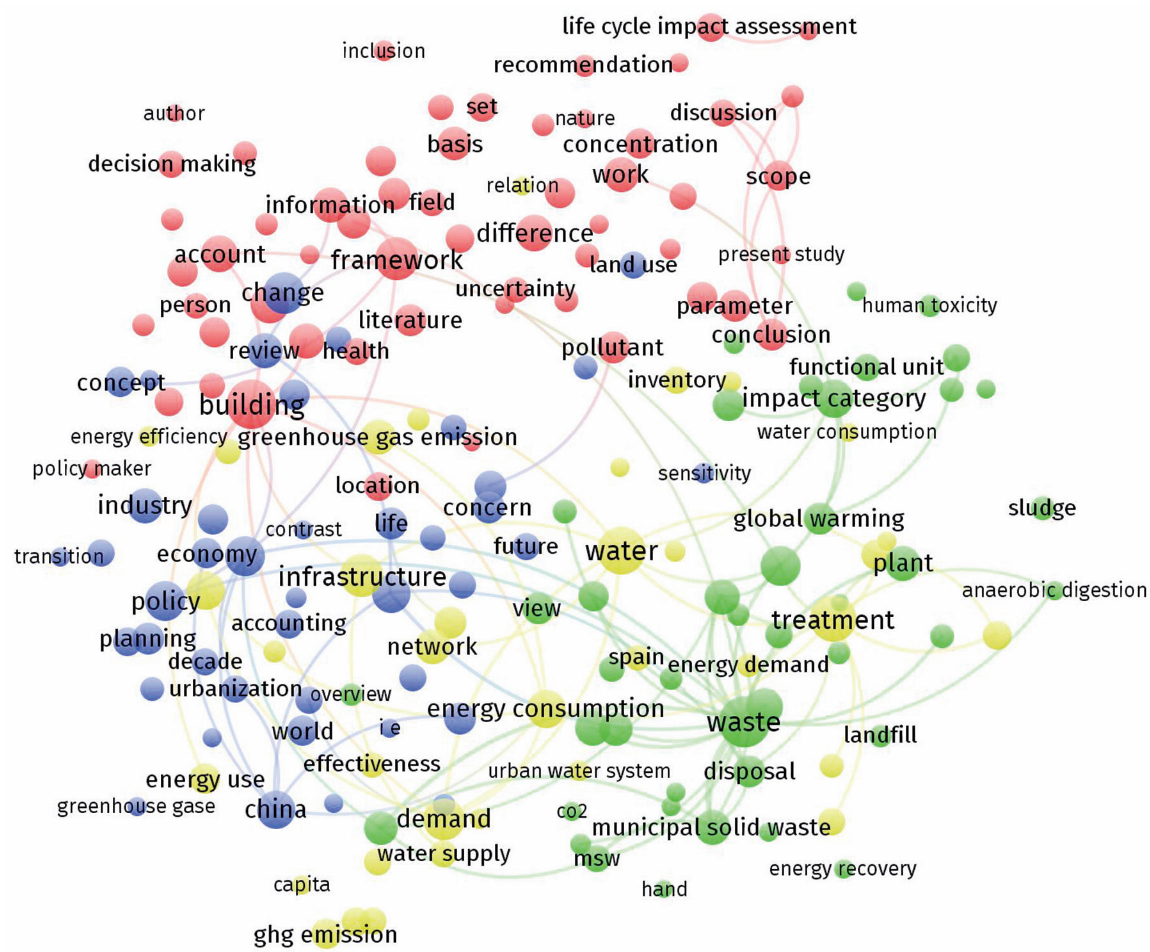
Year	TC-2017	TC/Y	Paper Title	Journal	Author	Topics	Country
2007	108	9	Comparative life cycle assessment of standard and green roofs	*Environmental Science & Technology*	Saiz et al.	Materials/ products	Canada
1998	104	9.45	Comparative environmental life cycle assessment of green roofs	*Building and Environment*	Kosareo et al.	Materials/ products	US
1999	102	5.1	Emerging trends in building environmental assessment methods	*Building Research and Information*	Cole	Design/ sustainability	Canada
2010	99	5.21	Building environmental assessment methods: applications and development trends	*Building Research and Information*	Crawley & Aho	Design/ sustainability	Finland
2009	97	12.12	Meta-analysis of greenhouse gas displacement factors of wood product substitution	*Environmental Science & Policy*	Sathre & O'Connor	Materials/ products	Sweden
2003	97	10.78	Relevance of simplifications in LCA of building components	*Building and Environment*	Kellenberger et al.	Materials / products	New Zealand/ Switzerland

author investigated the combination of clusters 1 and 4, with this focused research area redefined as ***urbanization and infrastructure planning***. Next, after combining clusters 1 and 3 together, one clearly defined focus area emerged: ***waste, water, and energy***. Cluster 2, however, did not appear to have a clear leading term like the other clusters and is relatively separated from the other three clusters. Furthermore, its research terms appear to illustrate a high-scale challenge related to LCA at the urban scale, including framework and decision-making, building, and health. Accordingly, we gave this area of focus a more general description: ***human factors and future uncertainty***.

4.1 Three Research Focal Points

The first focus area is urbanization and infrastructure planning, which covers urban form as well as density, spatial, and transportation planning. Infrastructural energy is defined as the embodied energy that goes into building an infrastructure. A number of studies have examined the impact of residential and commercial density on energy use and life cycle costs within urban regions (Anderson et al. 2015). Low-density suburban neighborhoods were found to have higher energy use and GHG emissions per capita compared to a high-density urban core (Borg and Groenen 2005, Newman et al. 1989, Zhang et al. 2010). Increasing population density while maintaining low-rise building typology tends to reduce the total energy demands and associated greenhouse gas emissions per capita (Borg and Groenen 2005). Another important finding was that a reduction in house size had a positive impact on decreasing overall urban energy and material use. Fuller and Crawford studied the impact of past and future residential housing

FIGURE 2. Term map representing the main research areas of LCA at the urban scale.



development patterns on energy demand, and results indicated that inner-suburban and inner-city apartment type buildings had the greatest potential to reduce a city's household-related energy consumption and greenhouse emissions—by 40–50%—associated with the use of public transportation (Zhang et al. 2010). The composition of urban space impacts—mixed use versus single use—also demonstrates the impact of use on energy efficiency. The results found that households in urban centers had lower emissions than their suburban counterparts; however, the urban sprawl could neutralize all the benefits from urban development and redevelopment (Zhang et al. 2010, Conte and Monno 2012, Turconi et al. 2014).

Besides housing infrastructure, transportation is another important category that has been studied extensively. The transportation infrastructure is responsible for an additional 63% of energy for on-road, 155% of energy for rail, and 31% of energy for air travel (Jones and Kammen 2014). High-speed rail systems, along with more advanced automobiles and aircraft, could reduce environmental impacts overall (Glaeser and Kahn 2008). Similar to the building scale, operational energy plays a critical role in infrastructure life cycle energy consumption as well as life cycle emissions. The studies on emissions have focused on the operational emissions of different transportation systems (e.g., public transportation systems) as well as emissions modeling that allows for comparisons between systems (Jones and Kammen 2014, Glaeser and Kahn 2008, Wiedenhofer et al. 2013, Chester and Horvath 2019, Chester and Horvath 2012). A key finding in the diverse research was a correlation between the urban density of transportation-associated energy consumption and an appropriate denser urban development trend. The denser urban development could reduce the overall energy use through infrastructure and network sharing (Naess 2009).

The second area is waste, water, and energy, which can be summarized as urban metabolism. An urban metabolism framework was developed with the aim to provide a foundational understanding of city resource uses and distribution (Naess 2009). Urban metabolism was originally developed by Wolman in 1965 as a methodology for measuring a city's overall energy, materials, water and nutrient inputs and outputs, and related processed and transformative energy and resources (Chester and Horvath 2012). Until now, the application of metabolism has been focused on energy consideration. Many studies on this have been conducted, including Ristimaki and team members who found that, in comparison to district heating, a ground source heat pump including 10% renewable energy was the most cost-effective method for an urban area with a 100-year life span (Newman and Kenworthy 2015). The shortcomings of the urban metabolism method lie in its lack of inclusion of upstream effects or a quantitative impact assessment regarding the local environment or human health. In a recent report produced by a research team from the University of California, Berkeley, the research team assessed how the life cycle assessment method could be integrated with urban metabolism to develop comprehensive energy and environmental inventories. Consequently, this approach could compensate the shortcomings of the traditional metabolism method.

The third area includes all topics relating to the complexity of urban issues, such as building-related health issues, decision-making, and associated information. Urban and built environments can be understood as complex social-ecological systems, where multiple related metabolisms interact at different scales (Berkes and Foke 1998), with the building representing just one scale in the holistic system. However, the cluster two (building) unlike others that are intertwined together, is isolated from infrastructure, planning, and energy consumption in other clusters. The disconnection of this cluster from others may be due to the emerging transdisciplinary research represented within the core of the building industry: decision science, uncertainty theory, parametric modeling, and economy. The integration of multidisciplinary research is still in the infant stage, where including human factors as part of the decision-making process has been challenging due to uncertainty. Therefore, it will take some time before this research focus is mature enough to reach out to other areas.

4.2 Most Influential Papers and Journals

Table 2 presents the top 15 most influential studies of LCA at the urban scale. The most influential journals are *International Journal of Life Cycle Assessment* and *Environmental Pollution*, with three papers each among the top 15 most-cited articles. The most cited article was "Comparing high and low residential density: Life-cycle analysis of energy use and greenhouse gas emissions" (Zhang et al. 2010). This paper was published in the *Journal of Urban Planning and Development* and has been cited 204 times since 2006, with a citation rate of 17 per year. This study provides an empirical assessment of energy use and greenhouse gas (GHG) emissions associated with high and low residential development. Three major elements of urban development were considered: construction materials for infrastructure (including residential dwellings, utilities, and roads), building operations, and transportation (private automobiles

TABLE 2. The most cited articles related to LCA at the urban scale, each year during 1990–2017.

Year	TC-2017	TC/Y	Paper Title	Journal	Author	Topics	Country
2006	204	17	Comparing high and low residential density: Life-cycle analysis of energy use and greenhouse gas emissions	*Journal of Urban Planning and Development-Asce*	Norman et al.	Urbanization and infrastructure planning	Canada
2010	191	23.88	Municipal solid waste management in China: Status, problems and challenges	*Journal of Environmental Management*	Zhang et al.	Waste/energy	China
2011	143	20.43	Solid waste management in European countries: A review of systems analysis techniques	*International Journal of Life Cycle Assessment*	Pires et al.	Waste/energy	EU
2011	133	19	Green roofs as a means of pollution abatement	*Environmental Pollution*	Rowe	Urbanization and infrastructure planning	USA
2008	126	12.6	A demand-centered, hybrid life-cycle methodology for city-scale greenhouse gas inventories	*Environmental Pollution*	Ramaswami et al.	Urbanization and infrastructure planning	USA
2011	115	16.43	Positive effects of vegetation: Urban heat island and green roofs	*Environmental Pollution*	Susca et al.	Urbanization and infrastructure planning	USA
2006	108	9	Comparative life cycle assessment of standard and green roofs	*Environmental Science & Technology*	Saiz et al.	Urbanization and infrastructure planning	Canada
2009	94	10.44	Source Separation: Will We See a Paradigm Shift in Wastewater Handling?	*Environmental Science & Technology*	Larsen et al.	Waste/energy	Sweden
2005	85	6.54	Developing sustainability criteria for urban infrastructure systems	*Canadian Journal of Civil Engineering*	Sahely et al.	Urbanization and infrastructure planning	Canada
2005	78	6	Environmental evaluation of different treatment processes for sludge from urban wastewater treatments: Anaerobic digestion versus thermal processes	*International Journal of Life Cycle Assessment*	Hospido et al.	Waste/energy	Spain

TABLE 2. *(Continued)*

Year	TC-2017	TC/Y	Paper Title	Journal	Author	Topics	Country
2008	77	7.7	Ranking potential impacts of priority and emerging pollutants in urban wastewater through life cycle impact assessment	*CHEMOSPHERE*	Munoz et al.	Waste/energy	Spain
2008	69	6.9	Assessment of land use impacts on the natural environment—Part 2: Generic characterization factors for local species diversity in central Europe	*International Journal of Life Cycle Assessment*	Koellner et al.	Human factors and natural challenges	Sweden
2009	67	7.44	LCA of selective waste collection systems in dense urban areas	*Waste Management*	Iriarte et al.	Waste/energy	Spain
2000	65	3.61	Environmental and economic analysis of management systems for biodegradable waste	*Resources Conservation and Recycling*	Sonesson et al.	Human factors and natural challenges	Sweden
1999	65	3.42	The Relevance of Green Building Challenge: an observer's perspective	*Building Research and Information*	Kohler	Human factors and natural challenges	Sweden

and public transit). The results also indicated that low-density suburban development is more energy- and GHG-intensive (by a factor of 2.0–2.5) than high-density urban core development, on a per-capita basis (Babaizadeh and Hassan 2013). The second most cited article was "Municipal solid waste management in China: Status, problems and challenges," published in the *Journal of Environmental Management*, with a total of 191 citations since 2010. This paper presents a study of municipal solid waste management status in China, and outlines challenges and suggestions (Conte et al. 2012). Since China has one of the densest urban areas, the study results could provide informative knowledge on waste management to other dense urban areas in other countries. The third most influential study was "Solid waste management in European countries: A review of systems analysis techniques," published in the *International Journal of Life Cycle Assessment*, with 143 citations since 2011. This research project also focuses on waste management but in a European context. Two research areas that were well-covered in the top 15 studies included *urbanization and infrastructure planning* and *waste and energy*. The third area, *human factors and natural challenges*, has not been extensively studied compared to the other two. This is due to the complexity and uncertainty of human inputs, as well as the unpredictability of some natural scenarios, representing a large gap that must be filled in the next five to ten years to catch up with rapid urbanization.

5. DISCUSSION

The effective improvement and utilization of life cycle assessment in the building industry, particularly the design phase, hinges upon identifying the tool's current barriers and gaps. The main deficiencies are described below: the building-centric approach, energy performance–centric approach, and lack of consideration for uncertainties.

In the current prevalent building-centric analysis approach, an individual building is regarded as a function unit, with individual building performance as the top priority. Analysis at the individual building scale treats the building as a stand-alone object, isolated from its context within the built environment (Anderson et al. 2015). This approach reflects the conception of the building as a consumer of resource and energy rather than as a producer of sustainability at different spatial scales (Turconi et al. 2014). Currently, life cycle energy consumption of buildings includes embodied, operational, transportation, construction, and demolishing energies. However, all of these are direct energies whereas several significant indirect energy types have not been included in the evaluation of building performance, which could represent a large missing portion. For instance, an office located in a dense urban space will result in much less energy being spent by occupants on commuting, due to widely available public transportation. However, if the exact same building is located in a suburban area, then much higher energy will be consumed by the occupants when commuting. Therefore, the same building could have a larger induced or indirect eco-footprint.

Another misleading concept, according to Pacheco's study, is the energy performance center: "A more energy-efficient building design does not necessarily coincide with more economical or more environmentally friendly designs" (Pacheco et al. 2012). The contribution of a building to sustainable development is assessed based on building performance (Kibert and Grosskopf 2012), with performance often quantified by energy performance and efficiency. Other indicators—such as indoor air quality, thermal comfort acoustic quality, visual comfort, and the occupants' well-being and satisfaction—are equally important to building energy performance (De Nooy et al. 2018, Rodríguez et al. 2013). Currently, some studies have tried to integrate those factors; however, a standardized procedure is still lacking.

The last knowledge gap involves the inclusion of temporal and human factors in LCA. Unlike other commercial products, a building has a much longer life span—about 50–75 years—and the use phase can have large environmental impacts, with multiple renovations and building upgrades related to building technology developments. Variations within the use phase can sometimes be greater than the total impact of the materials, construction, and end-of-life phase (Burnett 2007), and the variations are often caused by the users' decisions, or human factors. The most current LCA studies of built environments use a static model that assumes the impact factor is constant over the time span. This could result in an inaccurate projection, as building materials and systems are constantly changing and improving. Instead, the measurement should have a dynamic framework, rather than a static one, to accommodate technology development.

Based on the findings from the literature review, the author can conclude that significant progress has been made over the past twenty years of life cycle studies and assessment at the building and urban scales, respectively. Very few studies have been conducted on integrated LCA for buildings within an urban context; such studies could reveal hidden factors and result in new findings. In a study on urban development in Japan, research concluded that open space, such as parks and green areas, should be maximized to reduce life cycle greenhouse gas emissions from buildings. Kilbert and Grosskopf (2012) proposed that the ideal green building should have five major elements: integration with local ecosystems, closed-loop material systems, maximum use of passive design and renewable energy, optimized building hydrologic cycles, and full implementation of indoor environmental quality measures (Ge 2003, Kilbert and Grosskopf 2012). The building environmental assessment method (BEAMs), a building eco-labeling system, is an attempt to create a comprehensive assessment tool for green buildings in an urban context; LEED has also addressed certain induced impacts of individual buildings in a qualitative way. For instance, there are prerequisite requirements, such as LEED buildings needing to be located close to public transportation.

6. CONCLUSION

The built environment assists societies in meeting basic needs for shelter and security. Throughout time, it has increasingly developed to provide greater scales of comfort and amenities, albeit with considerable environmental impacts (Chester and Horvath 2009). Accordingly, a comprehensive LCA framework that integrates different scales of the built environment could play a major role in promoting the reduction of related ecological impacts. Most current LCA studies are confined to their own scale and scope while lacking consideration of other related factors, such as population density, urban density, transportation accessibility, open space, and public parks. It is imperative to synergize LCA at the building and urban scales together, using an integrated framework. The potential to use an integrated framework in both urban planning and a building design context is a relatively new development. At the building scale, early adoption of an integrated framework could help designers, architects, and engineers find optimized solutions through quantitative analyses and evidence. At the urban scale, the planning process is a matter of organizing land use and optimizing resources, materials, and the energy flow within city boundaries. Therefore, a future integrated framework could be used in two ways: either as an analysis tool to aid the decision-making of government officials or as a design tool for urban planners. There is also a need for the planning and design community—specifically, architects, engineers, and planners—to work together as a synchronized unit to set up work for a higher level of LCA integration in the built environment (Chester and Horvath 2012).

This research project identifies primary LCA research activities at the building and urban scales, followed by an explanation of the main research areas of focus and an outline of the knowledge gaps. Findings from this research project include other important environmental factors and also provide a foundation for further studies of an integrated framework incorporating LCA from different scales. There are limitations in this research, as LCA was divided into two macro-scales: building and urban. Significant differences exist between different micro-scale urban contexts—such as city, neighborhood, and district—thus there are specific considerations related to each individual scale. The next research steps will be to:

- develop an integrated framework to bridge LCA at the building and urban scales and to test and verify its applicability and accuracy,
- further study research foci and trends in different micro-scales in the urban context, and
- develop a method that could account for uncertainties caused in LCA by human and temporal factors.

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