A Bibliometric Review of Life Cycle Research of the Built Environment

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Keywords: life cycle assessment, bibliometric network data, building.

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.

1.0 BACKGROUND

Addressing the ecological impacts of the built environment requires an understanding of global trends in the building sector. 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 environmental impacts at the building scale (Utama et al. 2009, Treloar et al. 2000, Fay et al. 2000, Utama et al 2008, 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.

2.0 RESEARCH METHODS AND TOOLS

Bibliometric research is a research technique for studying science-based citation data, which originated in the early twentieth century. Citation analysis (CA) and Co-citation analysis (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, Moed 2006, Harzing et al. 2008). 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, Text data mining (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. 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/

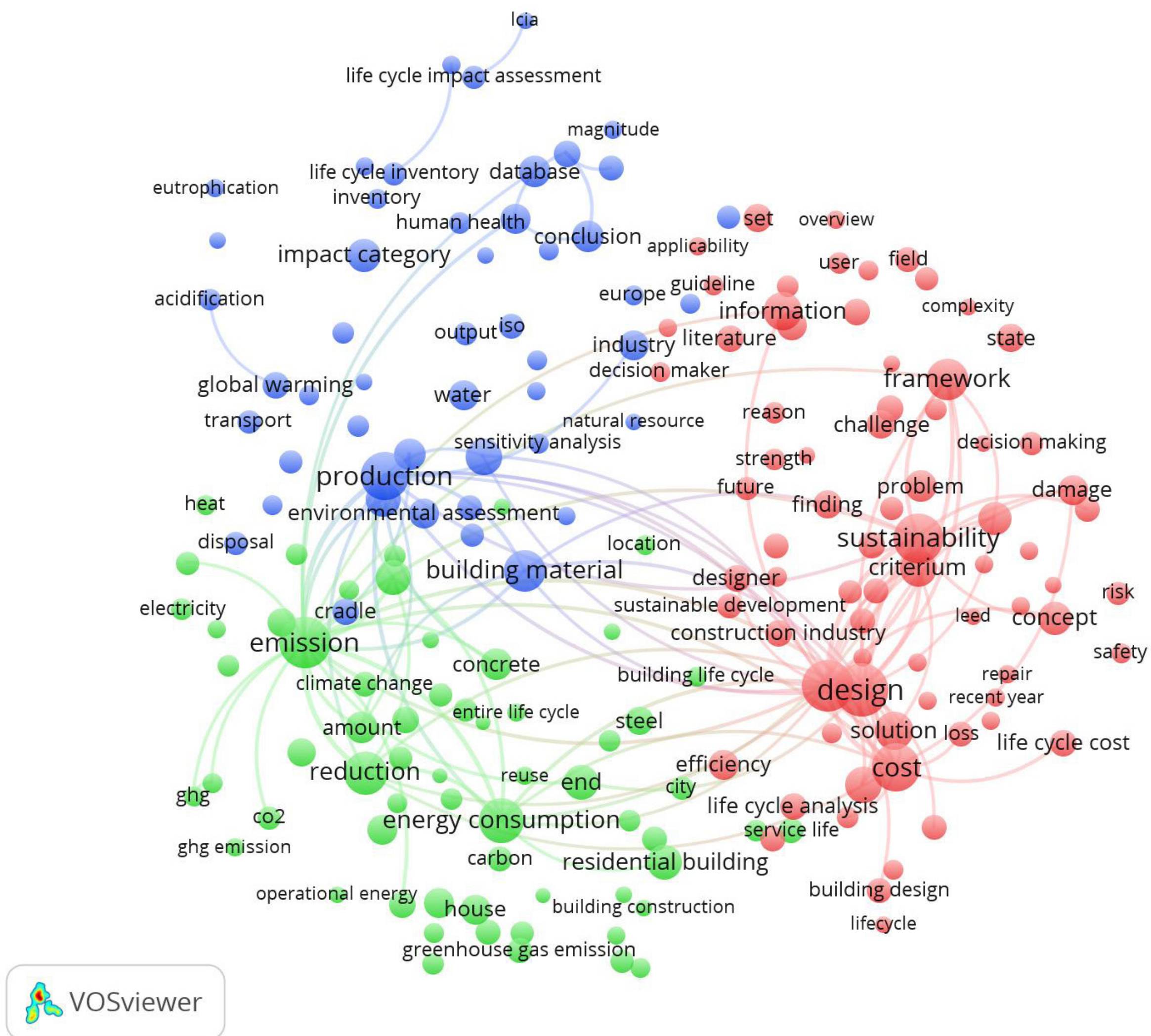

Figure 1. Term map representing the main research areas of LCA at the building scale

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. 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. 2009). 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. 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.

3.0 FINDINGS – 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 ` 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.

Base 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 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.

Cluster One: 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 CO2 emissions from the building industry (Chau et al. 2007, Guggemos and Horvath 2005, Bribián et al. 2009, 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. 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.

Cluster Two: 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. 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.

Cluster Three: Energy Consumption and Emission 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, CO2 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). 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).

4.0. FINDINGS- 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 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.

Cluster One: Urbanization and Infrastructure Planning

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. 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).

Cluster Two: Waste, Water, And Energy

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.

Cluster Three: Human Factors and Future Uncertainty

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 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.

5.0 DISCUSSION

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

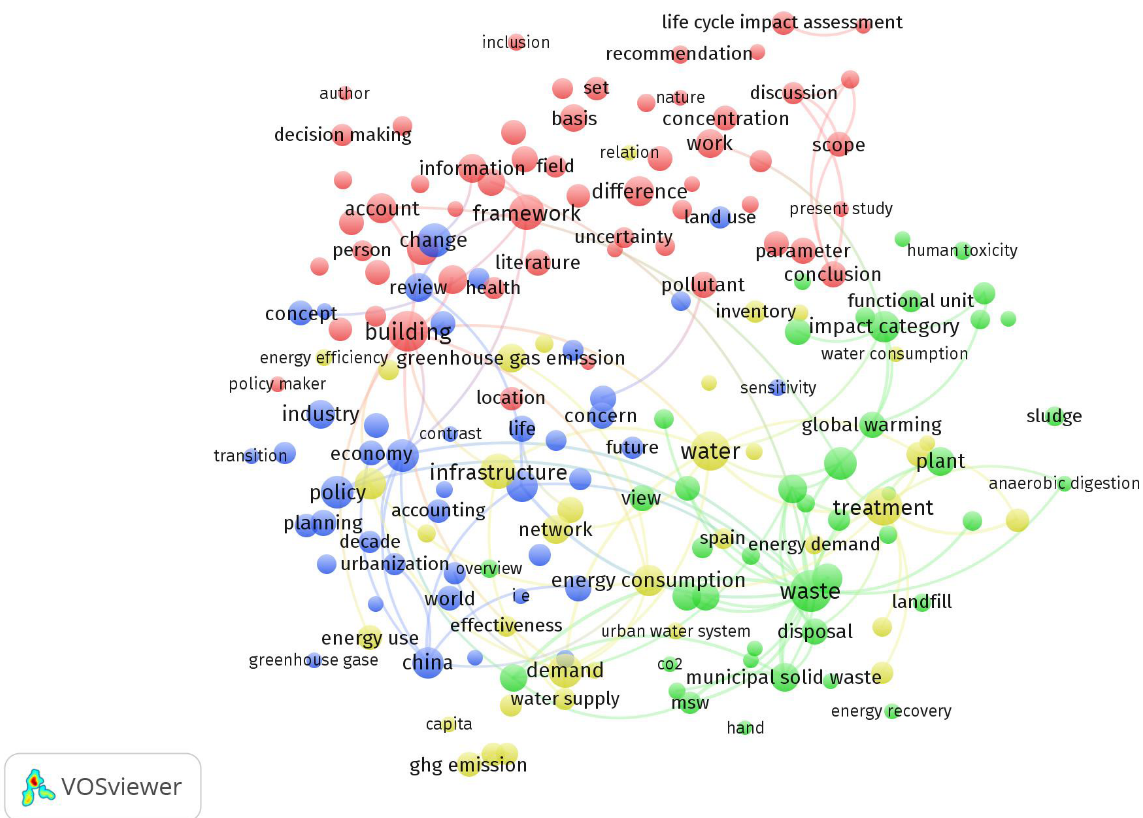

Figure 2. Term map representing the main research areas of LCA at the urban scale

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.

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.

6.0 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.

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