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Bim-based Life Cycle Assessment of Embodied Energy and Environmental Impacts of High-rise Buildings: A Literature Review

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Abstract Today 55 percent of the population in the world lives in urban areas which is expected to increase to 68 percent by the year 2050. In the cities, high-rise buildings as symbols of the modern cityscape are dominating the skylines, but the data to demonstrate their embodied energy and environmental impacts are scarce, compared to low- or mid-rise buildings. Reducing the embodied energy and environmental impacts of buildings is critical as about 42 percent of primary energy use and 39 percent of the global greenhouse gas (GHG) emissions come from the building sector. However, it is an overlooked area in embodied energy and environmental impacts of high-rise buildings. Life cycle assessment (LCA) is a widely used tool to quantify the embodied energy and environmental impacts of the building sector. LCA combined with Building Information Modeling (BIM) can simplify data acquisition of the building as well as provide both tools with feedback. Several studies recognize that the integration of BIM and LCA can simplify data acquisition of the building as well as provide tools with feedback. This article provides an overview of literature on BIM-based of embodied energy and environmental impacts of high-rise buildings. It also compares with different LCA methodologies. Finally, major strategies to reduce embodied energy and environmental impacts of high-rise buildings, research limitations and trends in the field are covered.

Keywords BIM, LCA, Embodied Energy, Environmental Impacts, High-rise Buildings

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1. Introduction

Global warming is now considered one of the greatest threats for the world. The average greenhouse gas index (AGGI) is increasing sharply, and CO_2 is by far the largest contributor to AGGI in terms of both amount and rate of increase (Haines, 2003). Because of its various anthropogenic GHG emissions, the construction sector is considered one of the key contributors to global warming. In the 2018 Global Status Report, buildings account for 39% of CO_2 emissions (see Figure 1). The construction industry accounts for 40 percent of global energy and product demand, as well as one third of global GHG emissions, according to the United Nations Environment Programme (UNEP, 2019). Today, building developers now tend to build high-rise buildings to optimize land use, particularly with rapid population growth in urban communities and stress due to land scarcity. A much denser and larger urban environment seems suitable for low urban energy use (Resch et al., 2016). High-rise buildings, however, typically require more energy and materials per floor area compared to low-rise buildings (Du et al., 2015; Trabucco, 2015), as a result of which total energy consumption and building related GHG emissions are expected to increase. Thus, to decrease energy consumption and GHG emissions, sustainable practices in high-rise building design have been developed in recent years.

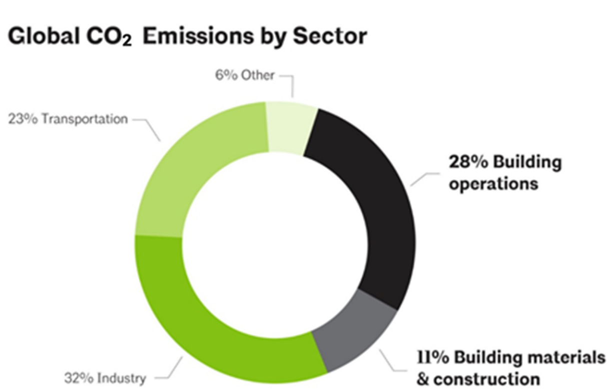

Figure 1. Global CO_2 emissions by sector, 2018. (IEA, 2018)

Building energy is divided into two broad categories: embodied energy and operational energy (see Figure 2.).

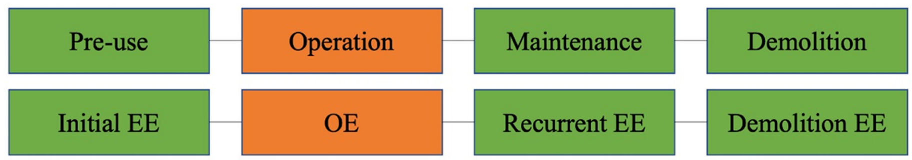

Figure 2. Life cycle energy use of a building is summation of EE and OE.

Many studies have been conducted to optimize operational energy, but quantification and optimization of embodied energy has not been extensively considered. There is a consensus in the literature that the significance of embodied energy will increase, particularly as the number of energy-efficient buildings is increasing (Copiello, 2016; Davies et al., 2014; Dixit et al., 2012). In fact, studies argue that, in most cases, operational energy efficiency is gained at the cost of increased embodied energy (Monteiro et al., 2016; USGBC, 2008). Embodied energy is the summation of initial, recurring and demolition embodied energies (Yohanis & Norton, 2002). The two major components of embodied energy are initial and recurring embodied energy. Initial embodied energy is the sum of the energy required for extraction and manufacture of a material together with the energy required for transportation of a material used for the initial building construction. The recurring embodied energy in buildings represents the sum total of the energy embodied in the material use due to maintenance, repair, restoration, refurbishment or replacement during the service life of the building (Chau et al., 2015).

2. Embodied Energy and High-rise Building

In a comprehensive cradle-to-grave definition, embodied energy is defined as the total energy used to construct, maintain, and finally demolish a building. Embodied energy is, therefore, the summation of initial, recurring and demolition embodied energies (Yohanis & Norton, 2002). The concept takes into account both upstream and downstream energy flows in a building's life cycle except the energy needed for the building to function. Initial embodied energy is the cumulative energy used for processing raw materials, manufacturing and transporting productions and components, and constructing a building. Therefore, initial embodied energy is all the energy used before the building is occupied, i.e., in the building life cycle pre-use phase. Recurring embodied energy is the energy that will sustain the building when it is in operation. It is the energy found in restoring or removing damaged materials and components. Recurring embodied energy is a feature of how occupants use the building, occupant maintenance requirements, building service life or life span, and materials and product performance, i.e., in the building life cycle use phase. Last but not least, demolition embodied energy is energy used to dismantle the structure at the end of its life cycle, recycle and reuse some materials, and dispose of others by moving rubble and waste to landfills or incinerators. Due to data availability issues, demolition embodied energy is a relatively unknown portion of the embodied energy content and therefore hard to discern. It also has a marginal share of a building's life cycle energy use (Azari & Abbasabadi, 2018).

In a 2004 study, Ding (Ding, 2004) performed a study of previous studies on the embodied energy content of buildings, finding that the initial embodied energy content varies 3.6 to 8.76 Giga Joule (GJ) per square meter of gross floor area (with a mean of 5.506 GJ/m^2) in residential buildings and from 3.4 to 19 GJ/m^2 of gross floor area (with a mean of 9.19 GJ/m^2) in commercial buildings. Recurring embodied energy content is shown by Ding (Ding, 2004) to range from 6.32 to 20.4 GJ/m^2. Ding (Ding, 2004) and Cole and Kernan (Cole & Kernan, 1996) suggest that demolition embodied energy constitutes 1-3 percent of initial embodied energy. Therefore, in calculating total embodied energy, most embodied energy studies choose to disregard the demolition phase of building life cycle.

In a more recent study, Aktas and Bilec (Aktas & Bilec, 2012) suggest that initial embodied energy accounts for 1.7-7.3 GJ/m^2 (with a mean of 4.0 GJ/m^2) in conventional residential buildings and 4.3-7.7 GJ/m^2 (with a mean of 6.2 GJ/m^2) in low-rise residential buildings. The higher average initial energy in high-rise buildings is due to thicker building skins and greater insulation usage (Aktas & Bilec, 2012). Aktas and Bilec (Aktas & Bilec, 2012) also indicate that the embodied energy of demolition phase ranges between 0.1-1 percent of total energy use in a residential building. In another review effort, Dixit (Dixit, 2017) examines the embodied energy of residential buildings and suggests that embodied energy can account for 0.9-16.3, 0.9-23.1, 0.9-19.2, and 0.9-6.6 GJ/m^2 in brick-, concrete-, steel-, and wood- built residential buildings, respectively. However, variations in recorded buildings' embodied energy content, as stated by various literature, result from inconsistent device boundaries, different embodied energy calculation methods, inconsistent technical and geographical representativeness, and variations in data source and quality.

Although anecdotal evidence suggests that building height directly affects embodied energy, there are few studies that analyze the buildings' embodied energy as a function of height (Bawden & Williams, 2015; Foraboschi et al., 2014; Ilozor et al., 2001; Resch et al., 2016). The increase in embodied energy with building height is primarily due to additional loads on the building structure, which results in the need for more energy-intensive building materials (Bawden & Williams, 2015; Foraboschi et al., 2014; Giordano et al., 2017; Ilozor et al., 2001). High-rise structures need stronger foundations compared to low-rise buildings due to their higher weight, which requires stronger foundation in lower stories and higher wind resistance. High-rise buildings are therefore also associated with higher initial energy embodied. The recurring as well as demolition energy embodied tends to be independent of building height variations and their share of total energy embodied is relatively insignificant (Resch et al., 2016).

Treloar et al. (Ilozor et al., 2001) analyze with various heights (3, 7, 15, 42 and 52 stories) the embodied energy of office buildings in Melbourne. The research analyzes the energy contained in substructure, superstructure, and finishes making significant conclusions. Firstly, the comparative assessment of a 42- and a 52-story building composed of core and steel columns reveals that an increase in height from 42 to 52 story increases the embodied energy from 18.0 GJ/m^2 to 18.4 GJ/m^2. It also indicates that high-rise buildings (42 and 52 stories) have in their materials about 60 percent higher embodied energy per unit gross floor area (GFA) than the low-rise buildings (3, 7 and 15 stories) that have been studied. Finally, the study shows that the rise in building height increases the embodied energy of the components of the structure unit (including upper floors, pillars, internal and external walls and staircases) while the variations in the embodied energy of other components such as substructure, roof, doors and finishes are not affected. In a similar study, Bawden and Williams (Bawden & Williams, 2015) undertake a comparative analysis of 3-, 4-, 7-, 11-and 21-story buildings in a similar study and developing a correlation between building height and energy usage. Their findings suggest that taller buildings are high-energy-intensive compared to low-rise buildings, and from 3 to 11- and 21-story buildings there is an estimated 30 percent increase in embodied energy.

Foraboschi et al. (Foraboschi et al., 2014) research the embodied energy of high-rise buildings with the central core of and either concrete or steel rigid frames and create an exponential relationship between building height and embodied energy. According to them, the dependence of embodied energy on building height is a double dependency; first, the more materials needed in larger buildings result in a directly proportional relationship between embodied energy and height, and second, the size of wind-load-resistant elements (and with less importance, the size of gravity-load-resistant system) result in further impact of the building (Foraboschi et al., 2014).

Though high-rise buildings are typically associated with high energy intensity due to the need for more energy-intensive materials to meet more stringent structural requirements, Foraboschi et al. (Foraboschi et al., 2014) show that the lower structural weight in high buildings does not necessarily translate into lower embodied energy. An example is the type of floor in high buildings that is considered to be the most critical component of the structure in these buildings in terms of embodied energy, yet the reduction of floor weight does not result in the reduction of embodied energy (Foraboschi et al., 2014). The lightweight floor structures, on the opposite side, can have higher embodied energy than the equivalent concrete systems (Foraboschi et al., 2014).

A review of embodied energy studies in large buildings shows similar limitations on other types of buildings as embodied energy studies. Issues such as ambiguous interpretations of embodied energy, incomparability of embodied energy results due to uncertain assumptions and contradictory methodologies, and data quality issues also restrict the degree to which embodied energy results can be generalized in large buildings. Furthermore, most inventory databases use in high-rise building energy assessments do not reflect high-rise building construction activities and therefore there is significant ambiguity in the embodied energy analysis of high-rise buildings relative to low-rise building construction, which needs to be dealt with in future research (Azari & Abbasabadi, 2018).

3. LCA Methodologies and Bim

Before BIM-based LCA methodology, there were three main LCA methods for embodied energy estimation process-based LCA, economic input-output LCA, and hybrid LCA. Process-based LCA is a strong methodology for embodied energy estimation in which the type and quantity of energy used in each and every step in a building life cycle. It generates building-specific embodied energy results and allows comparison of buildings, but the major disadvantages of this method are time-intensive, data uncertainty and underestimation of results due to narrow system boundary definition. Economic input-output LCA methodology was developed to address the limitations of process-based LCA. It utilizes annual input-output models of the US economy, as reported by US Department of Commerce, and relates monetary values of their industry sector to their environmental inputs and outputs. It generates sector-specific embodied energy results and extends system boundary which leads to more comprehensive results. However, it does not account for variation within sectors and does not allow comparison of sectors. The other disadvantages for this method are impossible process improvement and data uncertainty. Hybrid LCA methodology combines process-based LCA and economic input-output LCA with the objective of taking advantages of strengths and elimination the disadvantages of each method separately. It still has the potential inconsistency in methodologies, data sources and models, plus data uncertainty.

Furthermore, the development of methods that integrate BIM and LCA is growing. The importance of including LCA in BIM environment, especially in early stage of design is highlighted by Alvarez and Díaz (Antón & Díaz, 2014). Kreiner et al. have developed a systemic approach based on the LCA method, which concludes that improvements of sustainability performance of buildings can be carried out by integrating BIM with the developed approach (Kreiner et al., 2015). However, the development of the cradle-to-grave comprehensive BIM-based environmental sustainability simulation tool is still scarce (Wong & Zhou, 2015). The lack of reviews that analyze the integration of BIM and LCA is identified as a gap in the literature. For this reason, this study aims to review recent case studies that integrate BIM and LCA.

Digital tools based on BIM provide the potential to decrease the additional effort for LCA and speed up the process. Especially in the last five years, scientific studies about using BIM for LCA have been increasingly published in the literature and new software tools have been developed. Soust-Verdaguer, Llatas, and García-Martínez (Soust-Verdaguer et al., 2017) and Bueno and Fabricio (Bueno & Fabricio, 2018) provide an overview and review of the latest developments. Cavalliere (Cavalliere, 2019) provides a recent overview over building LCA including 28 commercial tools of which 7 use a BIM model. In addition, many researchers have developed their own workflows to connect an LCA database with a BIM software, for example linking Autodesk Revit (Stadel et al., 2011) or ArchiCAD (Crippa et al., 2018) with SimaPro or Excel (Soust-Verdaguer et al., 2018). In many recent studies, the visual programming plug-in Dynamo for Autodesk Revit is used to link the BIM model with an LCA database (Bueno et al., 2018).

The development of methods that integrate BIM and LCA is growing. Alvarez and Díaz (Antón & Díaz, 2014) underline the importance of including LCA in BIM environment, especially in early stage of design. Kreiner et al. (Kreiner et al., 2015) developed a systemic approach based on the LCA method. It concludes that improvements of sustainability performance of buildings can be carried out by integrating BIM with the developed approach. However, the development of the 'cradle-to-grave' comprehensive BIM-based environmental sustainability simulation tool is still scarce (Wong & Zhou, 2015).

An example of BIM-LCA integration is Tally (KT Innovation, 2014), a plug-in for Autodesk Revit that quantifies environmental impacts of building materials based on the LCA method, as well as allowing a comparative analysis of design options. Ma (Ma, 2022) utilized a BIM-based tool to analyze the embodied energy and environmental impacts of a reinforced concrete high-rise building in Chicago. In Ma's study, a framework is proposed to assess initial embodied energy, recurrent embodied energy and demolition embodied energy for high-rise building construction projects using BIM and implemented by designing and developing a BIM based tool (see Figure 3). The framework breaks down the embodied energy into four sections: product stage, construction stage end-of-life stage and module stage. It also evaluates the embodied energy in each section by using material quantity obtained from the BIM authoring tool and designated databases populated with transportation and construction information. The framework facilitates incorporation of the embodied energy assessment procedure into an integrated BIM-based design process by highlighting major contributors of embodied energy during different phases, which helps to integrate embodied energy as a parameter for building design considerations.

To implement the proposed framework a prototype is designed and developed. As mentioned previously, the data needed to determine the embodied energy content is categorized into two types: project data and common data. Since the project data is already captured in BIM environment, the real challenge is to realize the common data in the BIM environment. Revit is used as the BIM authoring tool in this study and all the project data is

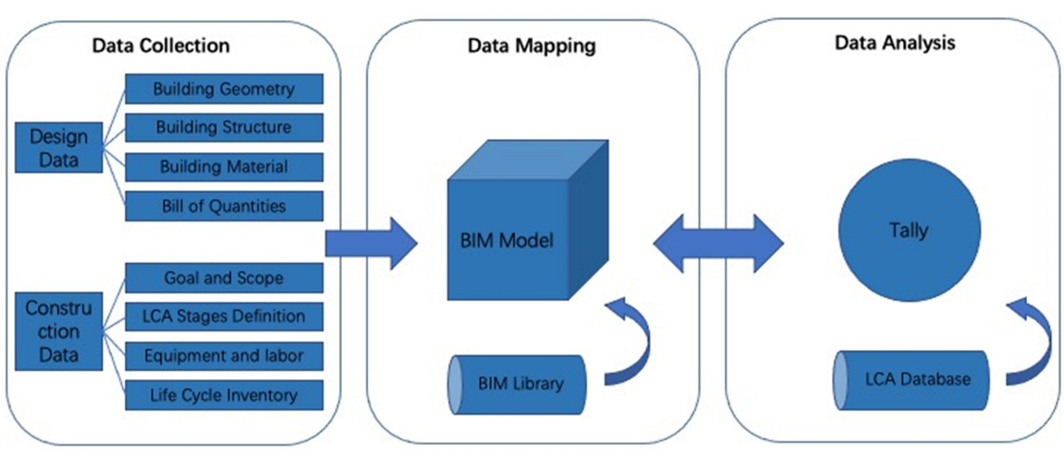

Figure 3. BIM-based LCA Method. (Ma, 2022)

assumed to be captured within the Revit environment prior to the functioning of the tool. Tally is used to develop the prototype in the form of an add-on for the Revit software to act as a tool to determine embodied energy content. Finally, statistical methodology is introduced to analyze the relationship between input and output data for all buildings studied (Ma, 2022).

However, the existing studies present methods for conducting BIM- based LCA in a specific design phase (Cavalliere et al., 2019). Usually, they are employed for a model with a relatively high level of development (LOD) of LOD 300 or higher in later design stage. No studies found in the literature apply these tools throughout the whole design phase. To provide feedback for designers and inform decision-makers, the LCA results need to be available throughout all design stages, especially in the decisive early design stage (Meex et al., 2018). However, they only provide the theoretical framework without a case study or real application. Cavalliere et al. (Cavalliere et al., 2019) provide a concept of linking several databases and provide a theoretical case study for the application of the framework. However, it is not applied during the design of a real building.

4. Conclusions

BIM-based LCA is essential for understanding and managing embodied energy and environmental impacts of high-rise buildings. The main contribution is developing a framework for architects and other decision makers to provide a more comprehensive image of embodied energy and environmental impacts of high-rise buildings. This framework applies to assess initial embodied energy, recurrent embodied energy and demolition embodied energy for high-rise building construction project using BIM and implemented by designing and developing a BIM-based tool. It also evaluates the embodied energy in each section by using material quantity obtained from the BIM authoring tool and designated databases populated with transportation and construction information. The framework facilitates incorporation of the embodied energy assessment procedure into an integrated BIM-based design process by highlighting major contributors of embodied energy during different phases, which helps to integrate embodied energy as a parameter for building design considerations. It can also offer an acceptable level of architect's friendly convenience and accuracy.

By using BIM-based LCA, the effort of calculating the embodied energy and environmental impacts of high-rise buildings can be reduced and therefore provide the potential for improving the LCA of high-rise buildings during the design phase. LCA databases become more and more available not only in the U.S., but also in the world. The BIM-based LCA can automatically calculate the embodied energy and environmental impacts of high-rise buildings based on a database and BIM software, such as BIM and Tally. The BIM-based LCA tool can be easily developed and used. Thus, the potential strategies solutions to reduce embodied energy and environmental impacts of high-rise buildings can be considered in the early design phase.

Due to the difficulties and challenges of collecting design and construction data of high-rise buildings, future work could improve by including more building materials and adding more case studies in different architypes to have a more comprehensive understanding of the embodied energy and environmental impacts of high-rise buildings. Future work could improve the data collection and assumption on the construction stage and extend to the operation stage by incorporating the simulation data for the occupant behavior. What is more, because some products and materials can be recycled and reused, such as steel, a cradle-to-cradle life cycle can be considered as a new boundary to develop more sustainable design and construct strategies on high-rise building.

So far BIM-based LCA still needs identifying various materials manually, which has huge time cost. Therefore, future research could focus on making the tool more intelligent by equipping it with machine learning or artificial intelligence to simplify the manual operating process and strengthen the automatic process. Also, results visualization needs to be emphasized in the future.

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