A Rapid Literature Review of Environmental Performance of Offsite Building Construction Industry

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ABSTRACT

The construction industry consumes about 36% of the total energy and releases up to 39% of global CO_2. If no appropriate measures are taken, the figure may double in the next two decades. Therefore, the construction sector is considering several measures to mitigate carbon emissions. In this regard, modular and panelized construction, which is collectively called offsite construction (OSC), is steadily gaining momentum. Several studies demonstrate that life cycle assessment (LCA) is a practical tool for evaluating the performance of OSC in greenhouse gas (GHG) emission reduction. Although a reasonable number of previous studies on OSC exist in the context of Canada, only a few apply LCA based on actual case studies. Realizing this fact, a collaborative research team from Concordia University, the University of Alberta, and NRC is undertaking an ongoing research project with the goal of decarbonization of the construction industry through OSC. As a foundation of this large ongoing research project, this study aims to review LCA related studies focusing on actual case studies in the context of OSC.

KEYWORDS

Modular and offsite construction; Life cycle assessment; Case study and greenhouse gas emissions.

INTRODUCTION

The construction industry contributes 13% to the global economy, and absorbs over 110 million workforces around the globe (Jayawardana et al., 2023). Contrariwise, the sector accounts for significant global resource consumption and greenhouse gas (GHG) emissions. According to the United Nations Environmental Program Report, the industry consumes about 36% of the total energy, and it releases up to 39% of global CO_2 (UNEP, 2019). The building sector alone consumes approximately 30%–50% of the total natural resources and generates about 35% of global solid waste (Jayawardana et al., 2023). According to UN report that the figure may double in the coming two decades if appropriate measures are not taken. Given these alarming figures, the construction sector is expected to consider a feasible solution that contributes to decarbonizing the sector. In this regard, modular and panelized construction, which is collectively called offsite construction

(OSC), is considered as a suitable strategy (Hong et al. 2016). The method not only improves the quality and safety of construction but also helps to improve GHG emissions in the sector. To evaluate these benefits, life cycle assessment (LCA) has been widely used in previous studies. In most of these studies, LCA was used to assess the energy consumption and environmental impacts of materials production, construction operation, and the end-of-life (EoL) phases. Although a reasonable number of previous studies exist in the context of Canada, only few studies was conducted based on actual cases. Realizing this fact, a collaborative research team from Concordia University, the University of Alberta, and NRC is undertaking an ongoing research project that aims to decarbonize the construction industry through OSC. As a foundation for this large ongoing research project, this study aims to review LCA related studies focusing on actual case studies in the context of OSC.

METHODOLOGY

To achieve its objective, this study employs a rapid literature review to assess the level of impact OSC can offer. This method is suitable when there is a need to collect information within a limited time (McCartney et al., 2017; Tricco et al., 2015). According to Tricco et al. (2015), the process in rapid literature reviews includes conducting an initial search using identified keywords and limiting the literature search based on additional criteria. With this understanding, the Scopus database, which is a compressive abstract and citation database that provides access to high-quality, peer-reviewed research, was searched using the following keywords; "Life cycle", "Life cycle assessment", "Sustainable", "Economic", "Environmental", "Framework", "Case study", "Off-site construction", "Prefabricated construction", "Industrialized construction", "Panelized construction", "Modular construction", "Precast construction", "Economic benefit", "Environmental benefits", and "Sustainable benefit" to find relevant publication from 2010 to 2024.

Following this process, 262 papers were obtained from the search engine. From the 262 papers, 81 papers were selected for further screening using Covidence, which is a suitable review platform that significantly reduces the reviewing time for reviewers. Finally, a total of 14 papers were identified from the 81 papers exported to Covidence. The summary of these studies is presented in Table 1.

LIFE CYCLE ASSESSMENT IN OFF-SITE CONSTRUCTION

LCA is a key scientific assessment method used to evaluate the potential for the environmental impact of a product or a system (ISO, 2006). In OSC, the method is commonly used to analyze environmental impacts from the phase of acquiring raw materials to the EoL phase (Antwi-Afari et al., 2022). For instance, Jayawardana et al. (2023) applied LCA to investigate the cradle-to-gate environmental performance of prefabricated construction methods as compared to traditional construction in developing countries. Similarly, Li et al. (2021) employed LCA to assess the carbon footprint of the prefabricated concrete stairs at the “materialization” stage, which involves the production, transportation, and construction sub-stages. Tian & Spatari (2022) have also investigated the environmental trade-offs offered by prefabrication compared to the traditional cast in-situ method using lifecycle assessment (LCA) focusing on primary non-renewable energy, global warming, and other environmental impact-related parameters considering a cradle-to-final construction stage. According to ISO (2006), the method involves four distinct stages that include

(1) defining the goal and scope, (2) life cycle inventory, (3) life cycle impact assessment, and (4) interpretation. The description and activities to be performed at each stage is presented hereunder.

Defining goal and scope

Most LCA studies in this section describes the research context, such as the scope of the research, its functional unit, and the system boundaries considered in their research (Anand & Amor, 2017; Ji et al., 2022; Jayawardana et al., 2023). The scope of most of the LCA studies focused on GHG emissions, which include both operational and embodied emissions. The choice of system boundary is another critical issue when defining the specific goal and scope of an LCA. In this regard, the study may consider either the partial phase (cradle to grave or cradle to gate) or the entire life cycle (cradle to cradle), as shown in Figure 1.

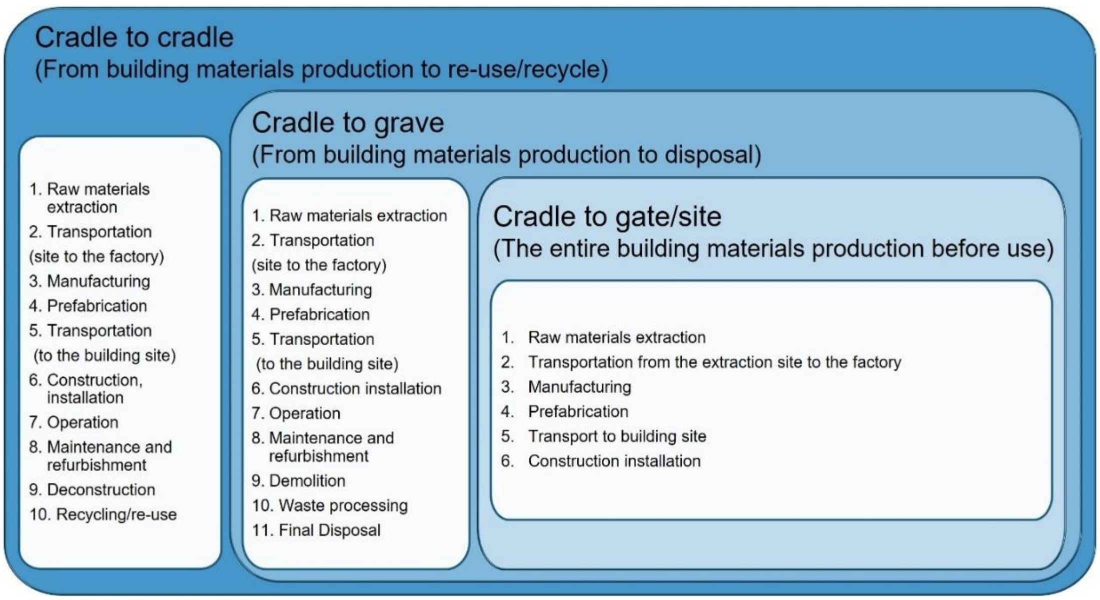

Figure 1. Ranges of system boundary.

Once the system boundary is determined, the next step is to decide which functional units should be considered. As shown in Table 1, the most widely used functional units in most of the literature are unit areas for the entire building and its components, and unit length/depth for the foundation and column. Few studies used other methods, such as the amount/quantity of materials and load capacity. Ji et al. (2022), for example, use load capacity as a functional unit in a case study of column production. The other aspects that must be addressed at this stage are LCA type and focus. Concerning LCA type, three major approaches are widely used in most LCA studies, namely process-based, input-output (I-O), and hybrid (Teng et al. 2018). According to Jayawardana et al. (2023), process-based LCA is the predominant LCA type used in most case study-driven studies. When it comes to LCA focus, the choice lies between the entire building, and building components like walls and columns.

Life cycle inventory

The selection of data sources and data collection process are critical to ensure reliability of research. The process involves identifying and compiling both input and output information associated with the goal and scope of the assessment/study defined earlier (Ansah et al., 2021). The typical data collected from both primary and secondary sources at this stage include energy consumption, types of products, materials used, emissions, and waste in the entire building lifecycle or its components (Ji et al., 2022). According to Anand & Amor, (2017), most of the primary data for LCA during the construction and operations stage are obtained from design, bill of materials, schedules, and related project records. The sources for generic/secondary building inventory data, on the other hand, include building industry databases and environmental product declarations (EPD). Since it contributes to the variation in the outcome, the age and the way the data is collected also is a concern in the life cycle inventory (Ansah et al. 2021). Due to this, obtaining quality data from both primary and secondary sources and identifying a suitable data collection method is still a challenging issue in life cycle inventory.

Life cycle impact assessment

The choice of impact category depends on the needs of the stakeholders (Anand & Amor, 2017). The assessment in OSC mainly involves quantifying the energy and environmental impact of a building or its components using various tools and techniques (Ansah et al., 2021). Some of the commonly-used tools and techniques to assess these impacts include generic techniques like SimaPro, Open LCA, and GaBi, or building-specific techniques, like BeCost, Eco Effect, and LEGEP-Life cycle assessment. A recent study by Ansah et al. (2021) used the CLM 2001 and cumulative energy demand (CED) within the Ecoinvent database v.3.5. Another study by Meireles et al. (2024), on the other hand, used the Environmental Footprint (EF) method, which was developed by the European Commission, and recommended characterizing the potential life cycle of environmental impact in similar studies.

Interpretation

This is a systematic step to evaluate the outcome of the lifecycle inventory analysis and life cycle impact assessment. The results from the above stages are interpreted and presented in a structured manner in the following sections.

DISCUSSION

This study conducts a literature review related to LCA focusing on case study-based researches in the domain of OSC. The review was conducted following the ISO 14040:2006 approach, which has been implemented in most of case studies reviewed in this study. The approach involves defining goal and scope, determining a life cycle inventory, impact assessment, and interpretation of the outcome. This study considered 14 papers identified through a systematic search. In this section the findings from these studies will be presented and discussed based on the ISO 14040:2006 four stages outlined above.

Defining goal and scope

As shown under the goal and scope column of Table 1, 50% of the case studies were focused on building comments, which include staircase, concrete piles, and partition walls, while the other 50% of the studies were related to completing buildings that range from concrete shade to high rise buildings. Regarding LCA types, from the three approaches (process-based, input-output, and hybrid), 85% of the case studies in the present study used the process-based approach, and only one study applied the hybrid approach. In terms of system boundaries, 65% of the papers considered the cradle to gate/site, and the remaining 28% applied cradle to grave. This indicates that almost all (thirteen out the fourteen) studies under consideration used the partial system boundary. None of these studies considered the cradle-to-cradle approach which is a system boundary that considers the whole life cycle. Among the various possible reasons for this, complexity may be the primary contributor. The other important issue that must be determined at this stage is a functional unit. In the studies under consideration, about 78% of the studies use unit area and the remaining studies apply load capacity and volume of concrete as a functional unit.

Table 1. Summary of the reviewed papers

Reference	Goal and Scope				Life Cycle Inventory (Primary Data Sources)	Life Cycle Impact Assessed and Main Findings
	LCA focus	LCA type	System boundaries	Functional unit		
Jayawardana et al., (2023)	Office building	Process	Cradle to gate/site	Unit area (in square meter or Square feet)	Bill of materials, project estimate and another project record	This study focused on a design-stage life cycle assessment using modular building unit in Sri Lanka to evaluate the potential environmental benefits. The results indicated that the strategy has the lowest environmental impacts in all categories, with a 63% reduction in potential global warming.
Li et al., (2021)	Concrete stair case	Process	Cradle to gate/site	Unit area (in square meter or Square feet)	Bill of materials and project estimate	This study investigated the carbon footprint of prefabricated concrete stairs at the materialization stage. The results demonstrate that the carbon emissions were mainly generated by raw-material consumption in the production stage and the carbon emission per unit cubic quantity was around 857.48 $kgCO_2/m^3$
Tian & Spatari, (2022)	Residential building	Process	Cradle to gate/site	Unit area (in square meter or Square feet)	Drawings, bill of materials and project estimate and other project records	This study investigates parameter uncertainty on greenhouse gas (GHG) emissions related to electricity production in China. The overall results reveal prefabricated construction achieved better environmental mitigation compared to traditional construction in terms of primary non-renewable energy, GW, terrestrial acidification, human carcinogenic toxicity, fine particulate matter formation, freshwater eutrophication, marine eutrophication with reductions of 11%, 11%, 12%, 15%, 16%, 16% and 2% respectively
Vasishta et al., (2023)	Building (precast building with and without sandwich panels and cast-in-situ building)	Process	Cradle to grave	Unit area (in square meter or Square feet)	Bill of materials and project estimate	This paper evaluates a precast building system with and without sandwich panel with respect the cast-in-place. The findings revealed that the precast building system, which is made of sandwich panel had 21% lower life cycle costs (LCC) compared to cast-in-place building system. The study also identified that the construction and operation phase also had 38% and 24% lower LCC compared to cast-in-place building systems respectively. In conclusion, the study reported a lower life cycle environmental impacts for precast building systems based nine indicators
Tavares et al., (2021)	Residential building	Process	Cradle to grave	Unit area (in square meter or Square feet)	Drawings, bill of materials and project estimate and other project records	In this study, a life cycle assessment was carried out to compare the prefabrication and conventional system of different structural materials for a single-family house. The result showed that prefabricated houses have up to 65% less embodied since most materials are recycled in prefabrication.
Li & Zheng, (2020)	Concrete pile products	Process	Cradle to gate/site	Unit area (in square meter or Square feet)	Bill of materials, project estimate and another project record	This study investigated precast concrete pile products and their carbon footprint at the construction stage. The finding from this study also revealed that about 73% of the carbon emissions from machineries were generated during construction stage
Luo et al., (2019)	Concrete piles	Process	Cradle to gate/site	Unit area (in square meter or Square feet) and unit length	Drawings and bill of materials	This study attempts to measure greenhouse gas (GHG) emissions of driven precast and cast-in-situ piles construction using two case studies in China. The results from the two-case study indicated that 113.04 and 107.46 $kgCO_2$ per pile per metre of excavated depth for case study 1 and 2 respectively. To the contrary, the study identified an increase for transportation in GHG emissions for precast piles as compared to cast-in-situ.
Sandanayake et al., (2019)	Commercial buildings	Process	Cradle to gate/site	Unit area (in square meter or Square feet)	Drawings, bill of materials and project estimate and	Unlike others, this study tries to quantify direct and indirect emissions associated with off-site construction and compare with traditional on-site construction considering two commercial buildings in China. The results indicate GHG emissions reduction of 8.40% for off-site construction.

					other project records	
Teng et al., (2018)	N/A	N/A	N/A	N/A	N/A	This paper examines a total of 27 cases of prefabricated buildings. The results show that the embodied and operational carbon emissions of these cases varied from 105 to 864 kg CO_2/m^2. Further interpretation of the result from these case studies also revealed that on average, 15.6% of embodied and 3.2% of operational carbon reductions were achieved through prefabrication.
Wan Omar et al., (2014)	Two story residential buildings	Process	Cradle to gate/site	Unit area (in square meter or Square feet)	Drawings	This paper assesses the carbon emissions of two construction approaches for a typical 2-storey residential structure in Malaysia considering both direct and indirect emission and the cradle to site system boundary. The assessment showed that a total emissions reduction of 26.27% using a precast wall panel system in the given structure. The study further pointed out that 90% of the emissions associated with these construction methods was originated from the material production.
Ingrao et al., (2014)	Concrete shade	Hybrid	Cradle to grave	Volume of concrete	Project recorded (such as fuel, electricity, production etc.)	This study analyzes the environmental impacts linked to the life cycle of a pre-cast concrete shed based on actual data from a construction site. The study was conducted with the objective of quantifying the resources, the materials and the energy demand for the shed construction, use and end of life phases. The results revealed that from the four phases considered in the system boundaries most inventories are observed in the construction phase since considerable amount of materials, fuels and resources such as concrete, steel, and electrical energy are used during these stages
Meireles et al., (2024)	Partition/Interior wall	Process	Cradle to gate/site	Unit area (in square meter or Square feet)	Drawings, bill of materials and project estimate and other project records	This paper assessed the life-cycle environmental performance of a prefabricated partition wall considering the cradle-to-gate options. For the specific scenario, the life-cycle impact assessment results generally indicate a superior environmental performance that ranges from 10 to 60% across evaluated categories. The study also identified that for both the prefabricated and the conventional systems, the material production stage is a predominant contributor for the impact.
Ansah et al., (2021)	High-rise building	Process	Cradle to grave	Unit area (in square meter or Square feet)	Drawings, bill of materials and project estimate and other project records	This study was conducted with the aim of developing BIM-based LCA method for prefabricated buildings. The developed approach supports automated assessments through all lifecycle phases of a prefabricated building. The approach was applied to evaluate the energy and environmental performances of a case building in Hong Kong. The case study validated the efficiency of the developed BIM-based LCA method.
Ji et al., (2022)	Apartment buildings	Process	Cradle to gate/site	Load capacity	Other sources	This study proposed a comparative environmental analysis for conventional and prefabricated construction techniques via BIM simulation. The comprehensive environmental evaluation was formulated in terms of gas emissions and material consumption. The results revealed that prefabricated construction demonstrates environmentally friendly performances in all aspects with the exception of acidification and mineral resource consumption.

Life cycle inventory

Since it involves numerous materials and processes, the life cycle inventory of a building is one of the complex tasks in LCA, which requires appropriate consideration. The typical information/data to be collected from both primary and secondary sources at this stage include energy consumption, types of products, materials used, emissions, and waste in the entire building lifecycle or its components (Ji et al., 2022). As shown in Table 1, the data sources for nearly all of the LCA studies are bills of quantity, drawings, and other project records, such as electricity and fuel consumption. In addition to these primary sources, Wan Omar et al., (2014) used secondary data from local and national inventory databases in Malaysia to complement their findings.

Life cycle impact assessment

The overall life cycle impact assessment considered in the present study demonstrates that OSC has a lower life cycle environmental and economic impact in compariaon to conventional construction. The findings from two case studies done by Sandanayake et al. (2019) and Tavares et al. (2021) revealed that OSC has a potential to reduce GHG emission by 8.4 to 65%. A recent study by Meireles et al. (2024) also confirmed a superior environmental performance of a prefabricated system ranging from 10 to 60% across various environmental impact categories. The result differs from the findings of Teng et al., (2018), which reported an average 15.6% of embodied and 3.2% of operational carbon reductions through prefabrication, considering 27 cases. The possible reason for such variance might be an increased awareness on the benefits of OSC and technological advancement over the last decades. Further interpretation of the result summarized in Table 1 indicated that from the four phases considered in the system boundaries (production of the raw materials, construction, use, and end-of-life) most inventories are observed in the construction phase (Ingrao et al., 2014). In agreement with Ingrao et al., (2014), Li & Zheng (2020) also indicated that about 73% of carbon emissions from construction machineries are generated during construction phases. This indicates that most of the carbon emission are originated from materials production and construction operations. The main reason for this is that both of these operations require a considerable number of materials and resources, such as concrete, steel, electrical energy, and water (Ingrao et al., 2014). In terms of economic performance, the present study pointed out that precast building system, which is made of sandwich panels, has the potential to reduce LCC by up to 21% compared to the traditional cast-in-place building system (Vasishta et al., 2023).

CONCLUSION

The main objective of this study was to conduct the rapid literature review aiming to identify quantitative information from case study-based researches in the domain of OSC. To achieve this objective, the study identified 14 case study-based papers and summarized their findings. The overall result from these case studies revealed that prefabricated or OSC has a significant role to minimize environmental and economic impacts in construction. Based on the summary of findings from these studies, prefabricated or OSC method has a potential of reducing up to 65% GHG emission and 21% LCC as compared to the conventional methods. As discussed in the methodology section, a rapid review is a type of knowledge synthesis in which certain components of the systematic review process are simplified or omitted. Hence, further studies should consider a more comprehensive systematic search/review focusing on case-driven research and a wide-ranging outcome.

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