Comparison of Carbon Emissions of Modular and Site-built Residential Construction

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ABSTRACT

The construction industry has significant environmental impacts by consuming natural resources, emitting greenhouse gas (GHG), and generating wastes. Hence, lowering the environmental impacts of residential buildings deserves serious attention. Over the past decades, modular construction has gained popularity due to its advantages: lower cost, lower waste, higher productivity, faster construction time, and lower environmental impacts. This prefabrication technique also provides mass production specifically to address the housing crisis. In addition, lower carbon emission of modular construction makes it even more popular in residential sector. This study aims to review literature on environmental impacts of modular residential construction and their comparison with equivalent site-built homes using the life cycle assessment method (LCA). The goal is to identify the gaps in existing knowledge and suggest research opportunities for future studies. The results indicate that there is a need to develop a comprehensive LCA framework to compare the environmental impacts of modular and site-built construction.

KEYWORDS

Modular construction, Greenhouse gas emissions, Site-built construction, Life cycle assessment, Environmental impacts

INTRODUCTION

The construction industry accounts for more than 10% of global Gross Domestic Product (GDP) (Alaloul, et al., 2021). Prediction shows that the volume of construction output will grow by 85% worldwide by 2030, with three countries – China, the United States of America (USA), and India – leading the way and accounting for 57% of all global growth (Robinson, 2018). The USA therefore will have a significant share of global growth. The construction industry added $943 billion value to the USA GDP in 2021, which is 4.1% of total GDP (BEA, 2021a, 2021b). In addition to economic gains, the construction industry has significant environmental impacts by consumption of natural resources, greenhouse gas (GHG) emissions, and waste generation, which are leading to global warming and climate change. Globally, the building sector accounts for 38% of all energy related CO_2 emissions (UNEP, 2020; WGBC, 2020). The GHG emission share of the building sector in the USA is almost 40% including operational energy (EIA, 2011). Furthermore, construction industry consumes 40% of total energy in USA (EESI, 2020).

Studies show that the inefficiency of current construction methods is one of the important causes of its environmental impacts (Fenner et al., 2018; Kibert, 2016). Sustainable construction organizations around the world are pushing the industry to meet the net-zero carbon building by

2050 to limit global warming and mitigate the overall emissions of the construction industry (UNEP, 2020). Consequently, finding efficient construction methods and strategies to mitigate emissions have become a priority. On the other hand, the residential sector is almost the biggest sector of building construction in value around the world, which contributes to the significant share of energy consumption and GHG emissions (Figure 1). This fact shows that lowering the environmental impacts of residential buildings deserves serious attention. Over the past decades, manufactured construction has gained popularity among sustainable construction experts due to its potential to reduce environmental impacts. In addition, manufactured construction has been an affordable option especially in the housing sector (Kim, 2008). Some industry experts and researchers state that manufactured construction has the advantage of lower waste generation, higher productivity rate, faster construction, and higher quality (Cao et al., 2015; de Laubier et al., 2019; Jin et al., 2020; Kim, 2008; Mao et al., 2013; Nazir et al., 2020; Papastamoulis et al., 2021; Pervez et al., 2021; Quale et al., 2012; Sandanayake et al., 2019; V. Tavares et al., 2021; Vanessa Tavares et al., 2019; Wuni et al., 2020).

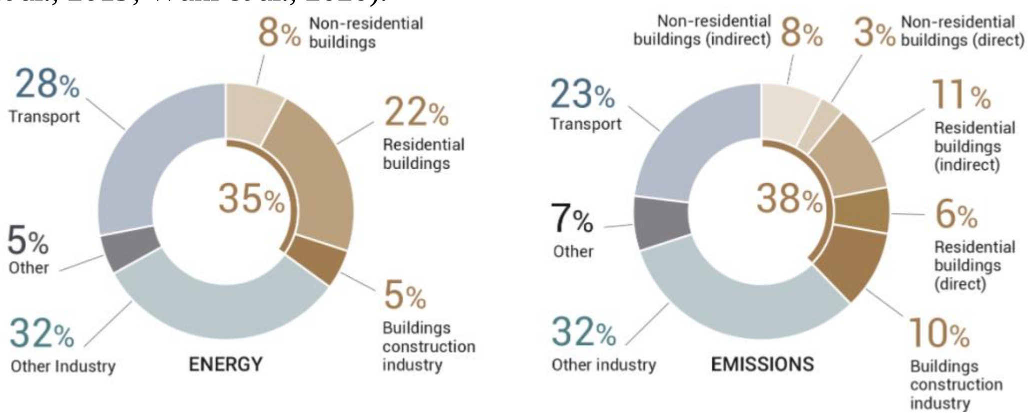

Figure 1. Contribution of residential building sector on energy consumption and carbon emission (IEA World Energy Statistic and Balances, 2020)

A site-built house is a traditional type of construction, in which materials and systems are transported to the construction site and fabrication and installation of the house take place on the site. Studies also utilize other terms such as conventional, traditional, and on-site construction instead of site-built construction (Bing, et al., 2021; Kim, 2008). Manufactured construction, on the other hand, is a process of producing building structures and components such as an entire home in a protected factory environment and transporting them in one or more sections to their destination for installation and assembly (Kibert, et al., 2017). Studies use off-site, modular, and industrialized construction as synonyms for manufactured construction. In the residential sector, modular homes are constructed off-site in a factory as a complete unit and shipped in a wide variety of layouts and designs to the homeowner's lot, where it is assembled and installed on a permanent foundation as would be the case for a site-built home (Kibert, et al., 2017). This study investigates the existing literature on comparing the environmental impacts of modular and site-built houses.

Life Cycle Analysis (LCA) is a tool to measure the environmental impacts of buildings and enable the construction industry to pinpoint sustainability targets. Life cycle analysis has been utilized to identify which materials and building components have the largest environmental impacts (Ortiz et al., 2009). Overall, studies show that LCA is a useful and valid component of a comprehensive and integrated green building design process (Quale et al., 2012). The life cycle inventory phase of LCA has been gaining more attention due to global warming issues (Quale et al., 2012). Life cycle energy in a building includes 4 phases: initial embodied energy, operational energy, recurring embodied energy, and demolition energy (Zeng and Chini, 2017). A comprehensive life cycle assessment of a building is typically considered a “cradle to cradle” approach that includes raw material extraction, transportation, manufacturing, construction, operations, repair, demolition, and end-of-life disposal and recycling (Fenner et al., 2018; Zeng and Chini, 2017). Zeng and Chini illustrated the different phases of LCA in a diagram (Figure 2). For instance, “cradle to gate” includes extraction of raw materials, transportation, and manufacturing processes. This paper aims to evaluate studies that used LCA to compare environmental impacts of modular and manufactured construction. The analysis aims to find the gaps and challenges in using LCA for such comparison.

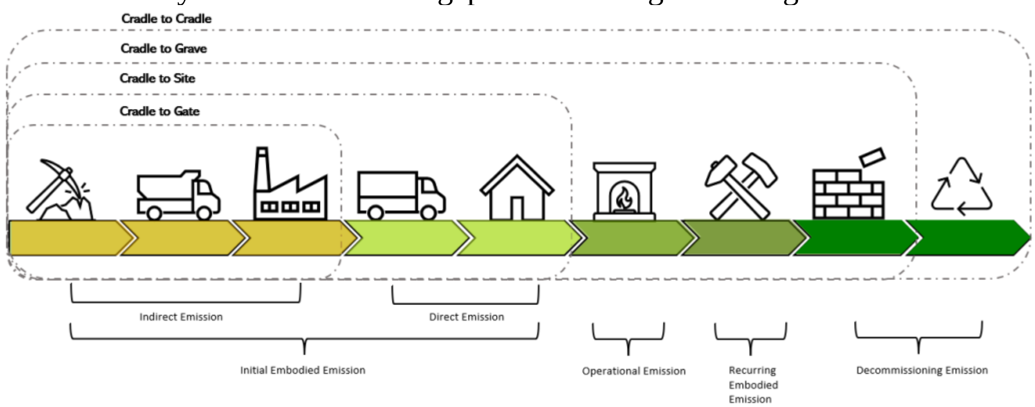

Figure 2. GHG emissions of buildings through their life cycle.

METHODOLOGY

This study applied a qualitative analysis in reviewing the studies that have used LCA to measure and compare the environmental impacts of modular and site-built residential construction. It utilized four-steps including: 1) identifying available academic databases, 2) creating sets of keywords related to the topic, 3) collecting and filtering the relevant articles, and 4) performing qualitative review and analysis. The first step was to identify the academic journals and databases that may contain any relevant materials on this topic. For this step, ‘Web of Science’, ‘SCOPUS’, and ‘Google Scholar’ were selected due to their comprehensiveness and free access through University of Florida library. The second step was creating three sets of keywords to find the most relevant articles. The first set of keywords identified the articles relevant to modular construction and housing, the second set was related to LCA and environmental impacts, and the third set was to find the articles covering site-built construction and housing (Table 1). Step three was identifying peer reviewed articles published within the timeframe of 2000 to 2021 that included the selected keywords. The three sets of keywords mentioned earlier were combined using operator “AND” to narrow down the articles to the more relevant publications. Then the title and keywords of each selected article were reviewed to confirm its relevancy. The last step was to review and analyse the selected articles to categorize and analyse their findings.

The search of the three databases for the selected keywords resulted in finding 13, 72, and 25 articles from WOS, SCOPUS, and Google Scholar, respectively. Review of the keywords and abstracts of the 110 identified articles revealed that only 37 of them studied the environmental impacts of modular or on-site residential construction. Further investigation showed that only 11 of the 37 articles utilized LCA to evaluate and compare environmental impacts of modular and site-built residential construction. A comprehensive analysis of these 11 studies was performed, which included a written summary of the aims, the research method, data collection approach, and findings. Findings of six articles and one report that had comparable LCA scopes and frameworks are discussed below.

Table 1. Literature review search parameters

Parameters	Settings
Set of search keywords	The first set of keywords: ALL= ("Modular Construction" OR "Modular Ho*" OR "Modular building" OR "Off-site construction" OR "Offsite construction" OR "Offsite hous*" OR "Prefab* Construction" OR "Prefab* building" OR "Manufactur* Construction" OR "Manufactured Hous*" OR "Industrialized Construction" OR "Industrialized Housing") The second set of keywords: ALL= ("Life Cycle Assessment" OR "LCA" OR "Greenhouse gas emission" OR "GHG emission" OR "Carbon emission" OR "Environmental impact" OR " Environmental assessment" OR " Life cycle performance") The third sets of keywords: AB= ("Site-built construction" OR "Site built construction" OR "Site-built hous*" OR "Traditional construction" OR "Conventional construction" OR "Onsite construction" OR "On-site construction" OR "Onsite hous*" OR "On-site hous*")
Time span	2000-2021
Citation index	Web of Science, SCOPUS, Google Scholar
Language	English

RESULTS

The literature search revealed that there are only few studies that have compared environmental impacts of modular and site-built residential construction. Six articles and one report are discussed below and their scope of life cycle analysis, the boundary conditions used, and their findings are provided.

Pervez et al. used a process-based cradle to gate method to compare environmental impacts of a modular single-family house with a conventional house with a similar floor plan in Karachi, Pakistan. The scope of this study was limited to calculation of CO_2, N_2O and CH_4. In addition, only major materials used in both construction methods were chosen to provide a fair basis of comparison. Pervez et al. calculated embodied GHG emissions of building materials, their transportation, resource consumption during construction of the building, module transportation from factory to construction site, and transportation of construction wastes to landfill. Results show 47% reduction of GHG emissions for the modular house compared to the conventional site-built unit (Table 2) (Pervez et al., 2021).

Table 2. Total GHG emission in modular and conventional construction (Pervez et al., 2021)

Source of GHG emission	Modular	% Contribution	Conventional	% Contribution	Reduction %
Embodied emissions of building materials	2607	75%	5419	83%	51%
Transportation to factory/site	721	20%	662	10%	-8%
Resource consumption	102	2%	411	6%	75%
Transportation to modules to construction site	15	0.4%	0	0%	-
Waste disposal	2	0%	8	0.1%	75%
Total	3449	100%	6501.	100%	46%

In 2012, Quale et al. reported a similar result based on comparison of environmental impacts of modular and conventional homes in the US using the life cycle assessment method. Comparable to the previous study, emissions from production of materials, their transportation, and waste disposal were calculated. In addition, transportation of working crews to the jobsite/factory were included. This study only calculated emissions of building materials that their amounts differed between the two methods of construction. The analysis revealed that environmental impacts from modular construction were, on average, 40% lower than those from on-site construction (Quale et al., 2012). Tavares et al. compared prefabricated and conventional single-family one-story residential buildings in Portugal. The prefabricated houses were made with light steel framing (LSF) or Wood framing (WF), and the conventional homes were made with concrete masonry blocks or blocks and bricks. The study used a cradle to grave life cycle assessment, which included emissions due to production of building materials, transportation of materials/labor, construction process, operational energy (50 years), waste generation of construction and demolition, and waste disposal. Material quantities, transportation distances, energy usage, labor, and equipment data were collected from construction companies and designers. The results show that in comparison with conventional homes, prefabricated homes of this study had up to 65% lower environmental impact. (V. Tavares et al., 2021). In 2011, Monahan et al. presented an LCA framework as a tool to conduct a partial cradle to site LCA for construction of an off-site panelized modular low energy timber house in the UK. Three different scenarios were modelled to compare their results. The scope of study included emissions due to production of materials and products, transportation of the materials and products to site, materials waste produced on site, transportation of waste to disposal, and fossil fuel energy used on site during construction and in manufacturing plant. This study only considered CO_2 as a main GHG gas to calculate GHG emissions. The study considered all building materials including doors and windows. The results indicated that the embodied carbon emissions of a house constructed using off-site panelized timber frame is approximately 34% lower than a conventionally constructed model (Monahan & Powell, 2011). Al-Hussein et al. compared CO_2 emissions of the construction stage of modular and site-built residential construction. A multi-unit, low-rise dwelling in Alberta, Canada was considered in their report. The scope of the study was limited to CO_2 emissions of construction activities including transportation of materials and crews to the construction site and factory, and construction equipment resource usage. The results showed that modular construction has 43 percent lower CO_2 emissions (Table 3). In addition, the study investigated the impact of season on CO_2 emissions in both techniques. The finding was that moving the construction process to a controlled factory environment would significantly lower the CO_2 emissions due to the on-site heating requirements over the cold seasons. (Al-Hussein et al., 2009).

Table 3. Comparison of the CO_2 emissions between modular and site-built residential construction

	Construction technique			
Item	**Site-built**	**Modular**	**Differences**	**Differences %**
Construction Time (Months)	10.8	6.8	4.0	37%
CO_2 emissions - construction process (Tons of CO_2)	98.9	56.3	42.5	43%
CO_2 emissions - Winter Heating (Tons of CO_2)	431.3	247.2	184.0	43%
Total Tons of CO_2	530.1	303.6	226.6	43%

In 2008, Kim selected a 1,456 ft^2 modular home and a conventional site-built (wood framing and roof truss system) home in Benton Harbor, Michigan to examine how the different construction and design methods of two types of housing influence their environmental impacts over a 50-year life span. Kim used LCA cradle to gate approach from initial raw materials acquisition through the manufacturing and production cycle, as well as energy consumption, to waste disposal over the construction phase (Figure 3). The study assumed that two types of buildings have been built with the same materials to simplify the calculation, and the only differences in building components were stud size, marriage walls and folding roof trusses. Based on the study, the modular home provided better environmental performance than the conventional home. The modular home consumes 4.6% less life cycle energy and emits 3% less greenhouse gas than the conventional home (Kim, 2008).

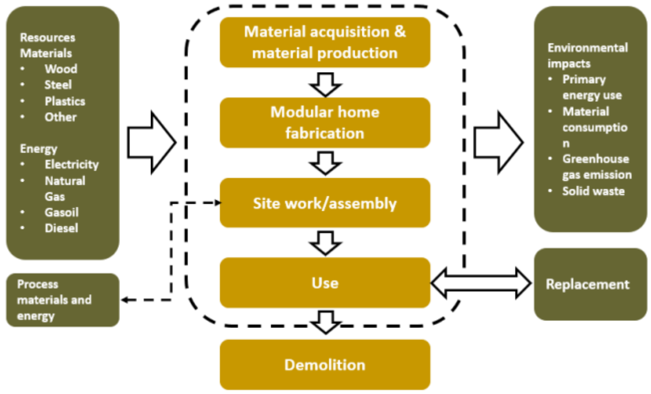

Figure 3. System boundary of the study (Kim, 2008)

Mao et al. in 2012 used cradle to gate method to compare carbon emission of a semi-prefab residential unit with a conventional unit in China. The boundaries of study was limited to the calculation of carbon emissions from embodied building materials (sand, cement, steel, brick, glass, and concrete), transportation of materials to the site and factory, transportation of the prefab units to the site, site energy consumption, and waste disposal (in the factory and on-site). In this research, water consumption data was added to the resource usage emissions. Results indicated that concrete materials had the highest emissions. Overall, carbon emissions in semi-prefabrication were 3.2% less than conventional construction (Mao et al., 2013).

DISSCUSSION AND CONCLUSION

Comparing the results of literature cited is not meaningful without considering the boundary conditions, building materials and components included, and other exclusions regarding energy consumption. The first important difference can be attributed to the selection of materials to be included in the study. The material selection ranged from cases that included emissions due to all building materials to the ones that only emissions due to differences in quantities of materials were included. This resulted in significant differences in percentage of emissions reduction for modular homes compared to the on-site built homes (Table 4). In addition, the location of home studied had a significant impact on the results. Selection of materials, transportation distances, and construction methods were varied based on the region.

Table 4. Comparing reviewed studies

Author	Location	Case study	Emission sources	Emitted gases	Activities	Scope
Pervez, H., Ali, Y., & Petrillo, A. (2021)	Pakistan	Built Modular House Unbuilt Traditional House	Fuel (diesel/oil) and electricity	CO_2, N_2O and CH_4	Embodied emissions of building materials, transportation of building materials, resource consumption during the construction, module transportation from factory to construction site, transportation of construction waste to landfill	Cradle to gate
Mao, C., Shen, Q., Shen, L., & Tang, L. (2013)	China	Semi-prefab: 216,000 m^2 Conventional: 187,836 m^2	Diesel, electric, water	CO_2, N_2O and CH_4	Embodied emissions of building materials, transportation of building materials, transportation of construction waste and soil, transportation of prefabricated components, operation of equipment, and construction techniques	Cradle to gate
Quale, J., Eckelman, M. J., Williams, K. W., Sloditskie, G., & Zimmerman, J. B. (2012)	United States	2000 ft^2-two story	Electricity, Gasoil, Fuel oil, Propane, Natural Gas	CO_2-eq	Embodied emission of materials; transportation of materials, workers, and units to site; energy usage; waste management	Cradle to gate

Monahan, J., & Powell, J. C. (2011)	UK	3-bedroom, 83 m^2 Scenario 1: MMC timber frame larch cladding. Scenario 2: MMC timber frame brick cladding. Scenario 3: conventional masonry cavity wall	Electricity, Mains gas, diesel	CO_2	Embodied emission of material, transportation of building materials, materials waste produced on site, transportation of waste disposal	Cradle to site
Kim, D. (2008)	United States	Built Modular House Unbuilt Traditional House	Electricity, natural gas	CO_2	Embodied emissions of building materials, transportation of building materials and crew, resource consumption during the construction, module transportation from factory to construction site, transportation of construction waste to landfill, operational stage, final disposal	Cradle-to-grave
Tavares, V., Soares, N., Raposo, N., Marques, P., & Freire, F. (2021)	Portugal	A 1-story house with 125 m2 living area. Prefab: Light steel framing and Wood framing Conventional: Reinforced concrete single-layer concrete block and Reinforced concrete double-layer brick,	Electricity	Overall environmental impact	Embodied emissions of building materials and transportation, operational stage, and end-of-life waste treatment	Cradle to cradle
Al-Hussein, M., Manrique, J. D., & Mah, D. (2009).	Canada	Multi-unit, low-rise dwellings	Electricity, fuel oil, gas	CO_2	Crew transportation, material transportation, resource consumption during construction by equipment, operation of equipment	Cradle to site (material embodied emission is excluded)

Despite all the varieties, literature review showed that modular construction has a lower environmental impact. The highlighted points of the literature review included:

- Embodied emissions of materials have the highest percentage of total emissions of building.
- Traditional construction materials used in each region may have negative environmental impacts. For example, use of concrete/masonry vs steel/wood.
- Selection of construction materials, construction techniques, and location of a building have major effects on its environmental impacts.
- Conventional site-built houses typically use brick and block, whereas modular houses use wood and light gauge steel framing. Therefore, the environmental impacts of modular houses are less than conventional houses.
- Embodied emissions of buildings materials and their transportation, construction waste disposal, transportation of prefabricated components to site, and resource and energy consumption during construction are the most common sources of emissions that were included in the reviewed literature.
- Prefabricated houses have lower emissions due to waste because of using modular components.
- Few studies included transportation of construction crew to the factory and to the construction site.
- One study included emissions due to building operations, maintenance, and end of life (Figure 4).

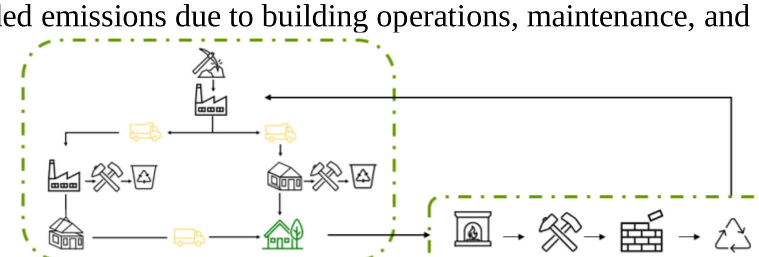

Figure 4. Adding operational stage to the LCA (Kim, 2008)

The results of the literature search showed the lack of a comprehensive LCA framework to evaluate GHG emissions in modular and site-built residential construction and a reliable method to compare their environmental impacts. Developing a framework for a comprehensive and efficient life cycle analysis of these two types of construction is essential to identify the major contributors to GHG emissions and find alternative construction materials/techniques to minimize their environmental impacts.

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