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Decarbonization of Modular Construction and LEED v5 Certification

Tarek SALAMA[1*], Arezou SADOUGHI[2], Jason MILLER[1], Mohammed ALSHARQAWI[1] and Yousif SAWA[3]

[1] *Assistant Professor, Department of Construction Management, California State University Sacramento, Sacramento, California, USA*
[2] *Assistant Professor, Department of Sustainable Technology and the Built Environment, Appalachian State University, Boone, North Carolina, USA*
[3] *Undergraduate Student, Department of Construction Management, California State University Sacramento, Sacramento, California, USA*
[*] *Corresponding author's e-mail:* salama@csus.edu

ABSTRACT
Modular and offsite construction (MOC) provides several advantages such as reducing cost and construction time as well as enhancing safety and quality. Decarbonization which is concerned with reducing or eliminating carbon emissions for manufacturing and construction is another advantage of MOC compared to traditional construction. MOC offers a promising approach to climate change mitigation by reducing greenhouse gas emissions, resource consumption, waste, and energy use. Manufactured prefabricated 2D or 3D modules in controlled manufacturing facilities allow modular construction to optimize material usage and minimize waste while reducing transportation of raw materials to construction sites, which reduces embodied carbon emission. For reducing operational carbon footprints, MOC also can be designed to be highly energy-efficient, while incorporating sustainable technologies and materials. Many studies conducted life cycle assessments (LCA) to evaluate the sustainability and decarbonization potential of MOC which are related to the total amount of carbon emissions through different life cycle phases including material production, construction, use of buildings, operation and maintenance, end-of-life stage, demolition and disposal. Green Building Certifications for decarbonized buildings can help in recognizing and assessing construction projects and buildings regarding their energy efficiency and sustainability. Many voluntary programs for certifications of green buildings exist in different countries such as the Leadership in Energy and Environmental Design (LEED), Green Star program, Building Research Establishment Environmental Assessment Method (BREEAM), etc. However, there is a lack of studies focusing on application of LEED certification for MOC. Hence, this study will investigate the practical application of LEED green building rating system for MOC.

KEYWORDS
Decarbonization; LEED; Modular and offsite construction; Green buildings; Carbon emissions

INTRODUCTION
Many studies included various advantages of MOC (Salama, 2019; Said et al., 2024; Salama & Said, 2024; Salama & Said, 2025). Decarbonization is another advantage of MOC and it means the reduction of carbon dioxide emissions as well as other greenhouse gas (GHG) emissions (presented as CO_2 equivalent) that were generated from different activities and processes including

manufacturing and construction. Life cycle carbon is the overall amount of carbon emissions for a product or service during its whole life cycle and it can be categorized into two main categories: 1) embodied carbon which represents carbon emissions generated from production, transportation, and disposal of components or materials of any product (Paneru et al., 2024); and 2) operational carbon, which represents carbon emissions generated from the use of buildings/products, such as energy use for its operation and maintenance activities. Decarbonization of construction would help in reducing climate change disasters such as drought, hurricanes, global warming, and flooding and also in improving air quality while enhancing energy efficiency and encouraging the use of renewable energy systems as well as utilizing sustainable building materials. This research aims to review the available studies of decarbonization in modular construction and green building certifications including LEED. Reviewing and discussing these can lead to a comprehensive understanding of the significance of practical application for MOC. The findings of this research work will help future researchers gain valuable insight for future steps toward developing decarbonization strategies and applications in the MOC industry.

METHODOLOGY

This methodology section outlines the methods employed to achieve the study's objectives. The research methodology is divided into three main parts: i) formulating a well-defined research question, ii) conducting a comprehensive literature review, and iii) presenting the findings of the literature review. To establish the research concept and ensure a sufficient number of articles for the review study, a preliminary search was conducted to identify relevant research publications and previous articles addressing the review topic. This involved identifying the research goal and selecting relevant keywords, such as "decarbonization, modular construction, LEED." The literature review was conducted on available databases from Google Scholar, focusing on journal papers and official research reports. The screening process involved title and abstract screening to identify the most relevant articles. Finally, the full texts of the considered articles were downloaded and analyzed.

DECARBONIZATION FOR MOC STUDIES

Some studies investigated environmental impact of MOC during its whole lifecycle, including design process, manufacturing activities, and deconstruction (Klammer et al., 2022; Paneru et al., 2024). These studies discussed MOC capability for reducing carbon emissions more than the reduction obtained from traditional construction by utilizing sustainable materials, efficient manufacturing processes, and energy-efficient designs. These studies highlight the importance of considering life cycle assessments (LCA) to evaluate sustainability and decarbonization potential of MOC, ultimately advocating for their wider adoption as a strategy to control climate change. Other studies investigated different aspects related to decarbonization of MOC (Lu et al., 2020; Klammer et al., 2021; Li et al., 2022; Pless et al., 2022). Lu et al. (2020) presented a bibliometric review for carbon emissions of green buildings through discussing various aspects such as sustainability, life cycle energy assessment. However, offsite construction relationship to this topic was discussed briefly in this research. Klammer et al. (2021) presented a research report prepared for the National Renewable Energy Laboratory (NREL) focusing on comparing different decarbonization strategies using "what-if" scenarios for every development stage, while utilizing emissions modeling, energy, and cost. Li et al. (2022) utilized a mixed-review method to assess current status of sustainability for MOC by reviewing publications related to six different themes including topics for environmental effect, energy efficiency and simulation, carbon emission, waste management, occupational safety and health, sustainable development, and life cycle analysis. Pless et al. (2022) presented a report for (NREL) discussing energy efficient design for MOC using various strategies including the selection of energy efficiency strategies, design of ideal net zero emissions (NZE) for Low carbon MOC, envelope thermal control, and envelope infiltration control.

Studies quantifying carbon emissions for MOC using life cycle analysis

Many studies focused on quantifying embodied carbon emissions by studying the entire life cycle of MOC projects (Xu et al., 2022; Xue et al., 2023; Wong & YT Tang, 2012; Lim et al., 2017; Teng & Pan, 2019). Paneru et al. (2024) introduced a comprehensive review for studies that focus on LCA for MOC which is based on the life cycle stages provided by the British Standards Institution (EN 15978:2011) (British Standards Institution, 2011). This standard includes five different stages as follows: 1) A1–A3, product stage; 2) A4–A5, construction stage; 3) B1–B5, use stage; 4) C1–C4, end-of-life stage; and 5) D, beyond. Table 1 provides a comparison between studies that includes different life cycle stages. Xu et al. (2022) and Xue et al. (2023) calculated embodied carbon for product and construction stages (A1–A5). Wong and Tang (2012) considered a (cradle to site) approach by considering stages (A1–A4). Lim et al. (2017), Teng and Pan (2019) presented carbon quantitative calculations that consider LCA from Stage (A1- C4). However, it was concluded that there is a clear research gap in calculating carbon emissions for stages of transportation, operations and maintenance, and end-of-life and beyond for MOC. Moreover, Wang and Sinha (2021) found that prefabricated buildings produce approximately 18% lower carbon emissions compared to conventional onsite construction and also it was concluded that carbon emissions may not necessarily decrease if prefabrication rate would increase. Hao et al. (2020) concluded that prefabrication would reduce carbon emissions by 15% due to manufacturing components in controlled manufacturing facilities that would generate less waste. On the other hand, Guo et al. (2022) indicated that when the prefabrication rate is around 35–40%, reduction of carbon emission would be maximized.

Table 1. Comparative table for studies against life cycle stages.

Year	Review article	Life cycle stage				
		A1–A3	A4–A5	B1–B5	C1–C4	Beyond stage
2023	Jayawardana et al.	✓	✓	-	-	-
2023	Griffiths et al.	✓	✓	-	✓	-
2023	Xue et al.	✓	✓	-	-	-
2022	Xu et al.	✓	✓	-	-	-
2022	Li et al.	✓	✓	✓	-	-
2022	Kim et al.	✓	✓	-	✓	-
2021	Qi et al.	✓	✓	-	-	-
2020	Wuni et al.	✓	✓	✓	✓	-
2020	Abdelmageed and Zayed	✓	✓	✓	✓	-
2020	Lu et al.	✓	✓	✓	-	-
2019	Teng and Pan	✓	✓	✓	✓	-
2018	Teng et al.	✓	✓	✓	✓	-
2018	Jin et al.	✓	✓	-	-	-
2016	Kamali and Hewage	✓	✓	✓	-	-

2017	Lim et al.	✓	✓	✓	✓	-
2012	Wong & YT Tang	✓	A4 only	-	-	-

GREEN BUILDING CERTIFICATIONS

Green building certifications serve as essential frameworks for assessing and promoting sustainability in the built environment. These certifications provide guidelines and benchmarks to reduce carbon emissions, enhance energy efficiency, and prioritize ecological responsibility throughout the lifecycle of a building. This section explores key certifications, comparing them across various criteria to understand their distinct approaches and contributions to decarbonization efforts.

Review on key green building certifications

Building Research Establishment Environmental Assessment Method (BREEAM) is one of the world’s leading sustainability assessment methods for buildings, developed in the UK. It evaluates the environmental performance of buildings based on various criteria, including energy efficiency, water usage, indoor environmental quality, and material selection, providing ratings from "Pass" to "Outstanding". While BREEAM acknowledges innovative building techniques like modular construction, it does not specifically prioritize it within its assessment framework (BREEAM, 2024). Green Star is an Australian-based certification system assessing the design, construction, and operation of buildings. It emphasizes categories like energy and water efficiency, indoor environmental quality, and emissions reduction, aiming to promote sustainable practices in the built environment. It supports the adoption of modular construction as a means of reducing waste and improving resource efficiency, although this is not a core certification criterion (Green Star, 2024). The Living Building Challenge (LBC) is a performance-based certification that requires buildings to meet rigorous sustainability criteria in seven areas, called “Petals” including energy, water, materials, and health. It strives for regenerative buildings that actively contribute to their ecosystems. Modular construction is supported as a potential strategy to achieve sustainability goals in areas like material life cycle impact and construction waste reduction (LBC, 2024).

The German Sustainable Building Council (DGNB) certification emphasizes lifecycle sustainability, focusing on environmental, economic, and sociocultural factors. It provides a comprehensive evaluation that integrates energy performance, material cycles, and user health and comfort. It considers modular construction as a viable approach for improving resource efficiency and adaptability over a building’s life cycle DGNB, 2024). Estidama, meaning "sustainability" in Arabic, is a certification system developed in Abu Dhabi. It is known for its Pearl Rating System, tailored to the region's environmental and cultural context, prioritizing water conservation, energy efficiency, and livability. It does not specifically address modular construction but encourages innovative construction practices that reduce resource consumption and enhance sustainability (Estidama, 2024). Green Mark is a Singapore-based certification promoting sustainability in the built environment. It focuses on energy efficiency, water efficiency, environmental protection, and indoor air quality, encouraging innovative green building solutions. Modular construction is encouraged as a sustainable construction approach, aligning with its goals to minimize waste and promote innovation (Green Mark, 2024).

LEED, a globally recognized green building certification program developed by the United States Green Building Council (USGBC), provides a framework for designing, constructing, operating, and maintaining environmentally responsible buildings. LEED-certified buildings aim to reduce carbon emissions, conserve water, improve energy efficiency, and enhance indoor air quality (USGBC, 2024a). LEED v5, the latest version, will be released in Q1 2025 after LEED v4 in 2013. LEED v5 aligns the built environment with a low-carbon future, addressing equity, health, ecosystems, and resilience. It reflects global urgency to tackle climate change, improve human well-being, and restore ecological balance while ensuring sustainable development is inclusive and resilient. LEED v5 is developed around three core areas of impact (Decarbonization, Quality of Life, and Ecological Conservation and Restoration) and five core principles (Decarbonization, Resilience, Health and well-being, Equity, and Ecosystems), aligned with global sustainability goals (USGBC, 2024b). LEED v5, designed by USGBC, will be implemented from 2025 to 2030 and updated every five years thereafter. It includes key rating systems like BD+C for new buildings and major renovations, O+M for existing buildings, ID+C for interior spaces, ND for community planning, LEED Homes for residential buildings, Cities and Communities for certifying sustainable cities and towns, LEED Zero for net-zero performance, and a new transit rating system. LEED v5 supports various climate change initiatives, such as the American Institute of Architects (AIA) 2030 initiative for carbon-neutral buildings and renovations, the American Society of Landscape Architects (ASLA) 2040 climate action plan for net-zero carbon emissions, and the Paris Agreement to keep global temperature gain below 1.5 degrees Celsius. More on the LEED rating system is discussed in the following section.

LEED RATING SYSTEM V4.1 & V5

Within the three core areas mentioned above, LEED v5 differs from LEED v4.1 by newly incorporating updated metrics, streamlining different processes for life-cycle assessments, and having a stronger focus on: carbon reduction, embodied carbon, health, resilience, and equity (Myles, 2023). In comparison to LEED v4.1, v5 introduces clearer metrics for carbon impact in all project stages and integrates guidance for aligning with global decarbonization goals. Every single credit and prerequisites in LEED v5 are connected to these three areas. For example, the Indoor Environment Quality Category emphasizes health and quality of life (Kaiterra, 2024), turning some incentive items into prerequisites such as MERV 13 air filtration for LEED BD+C. Adapting minimum requirements toward reducing embodied carbon emissions is another example. The LEED v5, Building Design + Construction (BD+C) rating system includes prerequisites for assessing whole-life carbon footprint, as well as the resilience of construction projects. USGBC released a Beta version for the Operations + Maintenance (O+M) rating system included in the LEED v5 to illustrate the restructured framework which shows the aforementioned three core goals in Table 2.

Table 2. LEED v5 Operations + Maintenance (O+M) prerequisites and credits according to core goals (USGBC,2025).

Climate Action			**Quality of Life**			**Ecological Conservation & Restoration**		
Prereq	Operational carbon projection	Req	Prereq	Assmt. for climate resilience	Req	Prereq	Site mgmt. policy	Req
Prereq	Sustainable transportation policy	Req	Prereq	Social impact assmt.	Req	Prereq	Water mgmt.policy	Req
Prereq	Energy and carbon policy mgmt.	Req	Prereq	Operational carbon projection	Req	Prereq	Water metering	Req
Prereq	Refrigerate policy & maint.	Req	Prereq	Occupant needs assmt.	Req	Prereq	Materials mgmt.policy	Req
Prereq	Minimum energy performance	Req	Prereq	Green cleaning policy	Req	Credit	Rainwater mgmt.	2
Credit	Sustainable transportation perf.	14	Prereq	Verif. of ventilation & filtr.	Req	Credit	Light pollut. reduction	1
Credit	Heat island reduction	1	Prereq	Environ. tobacco smoke ctrl.	Req	Credit	Water performance	15
Credit	Decarbonization & eff. plans	5	Credit	Operational plan. & response	1	Credit	Waste performance	7
Credit	Ghg emissions reduction	12	Credit	Equity within ops. & maint.	1			
Credit	Refrigerant impact reduction	2	Credit	Indoor air quality performance	13			
Credit	Grid harmonization	2	Credit	Occupant satisfaction survey	5			
Credit	Energy perf. & commissioning	14	Credit	Green cleaning	2			
Credit	Embodied carbon of int.materials	2	Credit	Integrated pest mgmt.	1			
Total	**Possible points**	**52**	**Total**	**Possible points**	**23**	**Total**	**Possible points**	**25**

Credit points for the three core goals (as shown in Table 2) can be summarized as follows:

1) Climate action (including decarbonization and resilience (nearly 50% of total points).
2) Quality of life (nearly 25% of total points).
3) Ecological conservation and restoration (25% of total points).

LEED CERTIFICATION FOR MOC

Studies on the LEED project case studies, interviews with stakeholders, and LEED-accredited professionals show that prefabrication results in obtaining LEED credits (Adams, et al., 2014; Waldman, 2022). Prefabrication comes with waste reduction which assists with the “Construction and Demolition Waste Management” section of the Material and Resources category. The materials and Resources category aim at reducing landfill waste. The USGBC review process however does not sufficiently allocate score points to the benefits of prefabrication. LEED certification can act as an incentive for general contractors to utilize modular prefabricated construction techniques. Achieving LEED certification for a building project is an appealing accomplishment for all the stakeholders involved in the project. In addition to waste reduction for the Material and Resources category, the use of prefabrication could contribute to other LEED categories such as “Sustainable Site”. For example, prefabricated techniques can reduce habitat and site disturbance (Khan and Jain, 2017). It is challenging to determine specific LEED credits that are achievable by modular construction. There are several aspects of utilizing modular techniques that benefit project sustainability. Among all, reducing the number of deliveries to the site, better thermal performance, reducing carbon impact, and better sound transmission and acoustic design, are examples of such benefits (Velamati, 2012). Yet, requiring them all to be specified for LEED credits requires more scrutiny and careful attention by Green Building Certification Inc. (GBCI). LEED v5 aligns with MOC practices because MOC produces less waste compared to traditional construction while LEED v5 rewards the low waste performance of building projects. Modular buildings also can be easily detached and reassembled in new locations, and this circular design is encouraged by LEED v5 for reusing existing building components.

DISCUSSION AND CONCLUSION

This paper presented an overview for decarbonization of MOC. The decarbonization of MOC was discussed by introducing several studies that investigate life cycle assessments (LCA) to evaluate the sustainability and decarbonization potential of MOC through different life cycle stages as well as the reduction of carbon emissions for utilizing MOC compared to traditional construction. Different types of certifications for green buildings were discussed along with its relevance to MOC with a special focus on the new LEED v5 certification that will be released in the first quarter of 2025 by USGBC. LEED v5 is presenting three core goals—Climate Action, Quality of Life, and Ecology—with the five core principles—Decarbonization, Resilience, Health and Wellbeing, Equity, and Ecosystem—demonstrating a shift toward a more holistic and integrated approach to sustainability compared to LEED v4. This framework places a stronger emphasis on environmental ecology and the well-being of end users, underlining how the next generation of green building certifications will require a broader focus on the interconnectedness of environmental and human factors. The transition from LEED v4 to LEED v5 reflects a broader, more integrated view of sustainability—one that acknowledges not only the environmental impact of buildings but also the role of the built environment in enhancing the quality of life, fostering resilience, and supporting social equity. By linking decarbonization with resilience, health, and ecosystem protection, LEED v5 promotes a more comprehensive and socially responsible approach to green building. For MOC, these updates are highly relevant. LEED v5’s expanded focus on the human and ecological dimensions of sustainability will require even greater attention to how modular buildings can be designed and constructed not only for performance but also for occupant health, community equity, and environmental stewardship.

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