Evaluating the Decarbonization Potential of Industrialized Construction: A Review of the Current State, Opportunities, and Challenges

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Abstract: Given the urgent need for decarbonization of the construction industry due to its pivotal role in global greenhouse gas emissions, industrialized construction (IC) has emerged as a promising technique to change the productivity, quality, and sustainability of construction. Although some evidence and case studies reveal that IC has distinct decarbonization advantages compared with traditional construction, there still is a need to analyze best practices, opportunities, and challenges in order to guide industry practitioners and to define key knowledge gaps. A systematic review was conducted following the three core steps: database search; research gap identification, analysis according to key lifecycle stages, and decarbonization themes. This synthesized existing academic works at the intersection of industrialized construction and decarbonization to provide a comprehensive understanding of decarbonization in IC. The findings show that although a significant amount of research focused on emissions during project stages A1–A3, there is a noticeable research gap in evaluating the carbon emissions associated with transportation, operations, and end-of-life attributes of IC. Moreover, the absence of real-time assessments during the B6–B7 operational stages impedes optimal carbon emission assessment. The verbosity of carbon estimation and tracking methodologies also adds challenges to ensuring that additional carbon impacts of IC are adequately offset by improved efficiency and lower onsite emissions. The potential of decarbonization of IC can be explored further by future research on the standardization of life-cycle assessments, development of continuous carbon-tracking methodologies, and application of alternative materials and new technologies. **DOI: 10.1061/JCEMD4.COENG-14609.** *© 2024 American Society of Civil Engineers.*

Practical Applications: The effectiveness of IC practices in reducing carbon emissions may vary, as deduced from the reviewed literature. However, the conscientious selection of materials characterized by low embodied emissions can contribute to a reduction in carbon emissions, applicable to both IC and non-IC projects. IC projects are uniquely positioned to achieve an even greater reduction in carbon emissions because of a unique process that innately offers waste reduction and product quality improvements. Although a considerable volume of research has focused on estimating carbon emissions, there appears to be a gap in tracking the precise quantity of emissions across various life-cycle phases within IC. Although there is considerable research on decarbonization in prefabricated components, research on specific life-cycle phases still is lagging. Furthermore, future research should prioritize investigating similar opportunities for three-dimensional (3D) volumetric systems.

Author keywords: Decarbonization; Industrialized construction (IC); Sustainability; Emissions reduction.

Introduction

Decarbonization refers to the reduction of carbon dioxide emissions and other greenhouse gas (GHG) emissions (expressed in terms of CO_2 equivalent) from human activities and related processes. The built environment accounts for 40% of annual global CO_2 emissions (Architecture 2030 2023). Therefore, decarbonizing the construction industry is essential for mitigating climate-induced disasters such as heat waves, flooding, landslides, and drought (Sharifi and Yamagata 2016). Many organizations and entire geographic regions are committing to achieving zero-carbon goals—e.g., Europe is attempting to become the first carbon-neutral continent by 2050 (European Commission 2023). Transitioning to a carbon-neutral society has become an urgent objective for improving how new infrastructure is built, considering the triple bottom line of sustainability: people, planet, and profit. With the current urbanization trend (it is forecast that more than 70% of the global population will migrate to cities), resources are now being consumed at about 2 times the rate they are produced (Zhang 2016). The extraction of natural resources will increase over time to meet the demand for mass migration to the cities, which is unsustainable (Huang et al. 2018). A promising approach to address our built infrastructure needs (e.g., mass production in a sustainable manner) is industrialized construction (IC).

IC focuses on strategies to improve the design-to-construction process through intelligent manufacturing and automation (Qi et al. 2021). It takes on many forms, including three-dimensional (3D) volumetric modular construction, two-dimensional (2D)

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prefabrication, robotic manufacturing, and intelligent on-site factories. Using these techniques, it is possible to reduce project schedules and labor while maintaining high quality standards and vastly improving the sustainability of constructed products (Liu et al. 2023). Intrinsic scalability, high demand, and unique local labor challenges are inherent issues in many built infrastructure projects, which IC is effective in addressing (Bertram et al. 2023). Through the application of IC, well-crafted manufacturing and automation can lead to schedule and cost savings of about 20%–50% (Bertram et al. 2023). In addition to the up-front cost and schedule benefits of IC, the unique restructuring of components also provides for a much more robust potential for carbon emissions reduction. Although IC has the potential to reduce life-cycle carbon, the actual amount of decarbonization depends on the specific techniques and materials used in the manufacturing process, as well as the transportation and assembly of the final product. Numerous studies (e.g., Jayawardana et al. 2023) compared the environmental sustainability of IC buildings in developed and developing economies, Li et al. (2022a) analyzed sustainability themes and research trends in IC, and Lu et al. (2020) provided insights into strategic and technological innovations for green building practices through a bibliometric review method and discuss the various sustainability attributes of IC projects, but no studies to date have presented a thorough, comprehensive review of decarbonization of IC (1) from a life-cycle standpoint; and (2) using decarbonization tools and approaches. This study advances the understanding of decarbonization of IC by examining each life-cycle stage: product development, prefabrication, construction, utilization, and end-of-life considerations. Moreover, it explored embodied carbon estimation, quantitative and qualitative decarbonization strategies, and relevant policies influencing decarbonization efforts.

This research provides a comprehensive state-of-the-art review of the current state of decarbonization in IC and explored its potential for reducing carbon emissions in building construction projects. By aligning with the key life-cycle stages outlined in BS EN 15978:2011 (British Standards Institution 2011), a commonly used framework in the industry, this study analyzes the stages of the IC process that have received the most research attention and those which lag. These stages in BS EN 15978:2011 encompass product development (manufacturer-focused), prefabrication (fabricator-focused), construction (contractor-focused), use (facility manager-focused), and end-of-life considerations (owner's decision). Understanding the nuances of each life-cycle stage and identifying existing research limitations is crucial for discerning the decarbonization potentials within IC. Such insights will provide valuable lessons learned and inform important considerations for researchers and practitioners seeking to optimize their approach to decarbonization in construction projects. Furthermore, this review highlights key barriers and challenges in the decarbonization of IC, which will be helpful for both academia and industry to tailor their attention to the gaps. By synthesizing existing knowledge and identifying areas for improvement, this research advances the collective understanding of decarbonization in IC and facilitate informed decision-making for sustainable construction practices.

This paper is structured as follows. Firstly, background on the IC of buildings and decarbonization efforts in construction is presented. Secondly, the existing literature is reviewed to identify gaps in the knowledge of the decarbonization of IC. Lastly, a systematic literature review is conducted, focusing on the previous research that examines IC from the decarbonization perspective. This review examines previous research on IC decarbonization from a life-cycle perspective and discusses decarbonization tools, strategies, and challenges.

Background

Industrialized Construction of Buildings

The term industrialized construction can be unclear because it often is used to describe approaches such as off-site construction, prefabrication, modular construction, or innovative manufacturing. Often, IC is manifested in unique taxonomies depending on geographic location. Table 1 lists some of the common terms used to describe IC across different regions. Although some of these terms are indeed considered to be interchangeable (e.g., off-site production and off-site manufacturing), other terms denote unique applications of IC (e.g., industrialized building system or prefabricated housing). Despite different terms, IC inherently is based on the premise of improving the design-to-construction process by adopting intelligent manufacturing and automation (Qi et al. 2021).

IC applied specifically to building construction often involves standardized and mass-produced building components that are manufactured to precise specifications and quality standards in a controlled environment. These components can include walls, floors, roofs, and even entire 3D volumetric modules or units of buildings. Industrialized building techniques can be applied during the design, production, transportation, and assembly of building components and structures. IC of buildings takes over a range of project delivery mechanisms (Qi et al. 2021). The construction industry continues to face challenges such as labor shortages, rising material costs, and project delays. The use of IC and Design for Manufacturing and Assembly (DfMA) principles has allowed for greater efficiency, standardization, and quality control in the construction process, leading to faster project completion times and cost savings. In addition, the ability to manufacture building

Table 1. Terms used to describe different forms of IC

Country	Common IC terminology	References
US	Prefabrication, preassembly, modular construction and offsite fabrication (PPMOF)	Song et al. (2005)
Canada	Modular construction	Kazem-Zadeh and Issa (2020)
UK	Modern method of construction (MMC)	Pan et al. (2008) and Koronaki et al. (2021)
Sweden	Industrialized construction	Larsson et al. (2014)
Germany	Offsite production	Attouri et al. (2022)
France	Industrialized construction	Attouri et al. (2022)
China	Industrialized construction	Li et al. (2020) and Liu et al. (2023)
Japan	Prefabricated housing/components	Attouri et al. (2022)
Malaysia	Industrialized building system (IBS)	Kamar et al. (2011)
Singapore	Prefabricated prefinished volumetric construction (PPVC)	Rahman and Sobuz (2018)
Australia	Offsite manufacturing	Attouri et al. (2022)

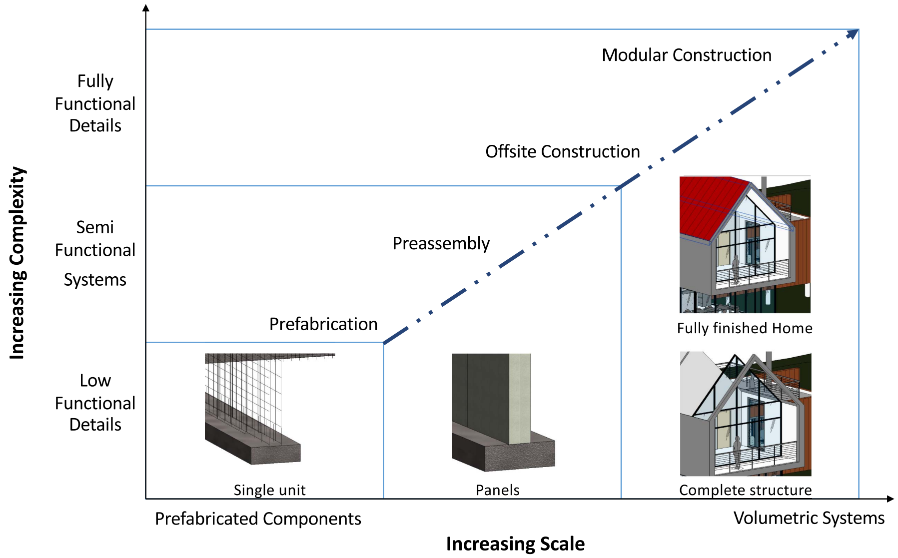

Fig. 1. Complexity and scale of IC in the construction sector.

components in a controlled environment also has been shown to improve safety on construction sites by reducing the need for on-site work. As technology and materials continue to advance, the range of off-site manufacturing in the construction sector is expected to expand further. Various levels of scale and complexity exist in IC, such as components production to the systems assembly (Fig. 1).

The complexity of IC often is influenced by the degree of customization required for the building design. Standardized modules designed with limited customization options can be easily mass-produced, resulting in faster and more-efficient construction times. However, more-complex designs with unique specifications and features may require specialized manufacturing and assembly techniques, which can increase project costs and construction time. IC approaches also can vary in terms of the level of finishing and fit-out that is completed off-site (Fig. 1). For example, some modular units include only basic structural elements and services, and interior finishes and fit-out are completed on-site. Others may include complete interior finishes, fixtures, and equipment, allowing for faster occupancy of the building. Market demands such as lower costs and faster project schedules combined with labor shortages in advanced economies are driving the construction industry toward innovative solutions such as IC (Hatami et al. 2022). Fragmented supply chains, persistent scarcity of skilled labor, and changes in market characteristics necessitate more-efficient building methods. Emerging technologies, new materials, standardized codes, and a focus on safety and sustainability are shifting construction from on-site installations toward modular and product-based solutions (Bertram et al. 2023). IC also has the potential to reduce carbon emissions throughout a building's life cycle. One study showed that a modular construction project in London led to 45% less carbon emissions than traditional methods, surpassing the targets of the Royal Institute of British Architects (Lowe 2022). IC enhances decarbonization by optimizing manufacturing and transportation, simplifying logistics, and offering better control in a managed construction environment. This controlled environment encourages a reduce–reuse–recycle approach, minimizes rework, and shortens operation and maintenance cycles. Clean or on-site energy can be used in production, and prefabricated components reduce waste and promote material reuse. This not only curtails emissions in buildings, but also positively impacts the broader economic value stream.

Decarbonization in Construction

Buildings contribute to almost 40% of global greenhouse emissions. Of these emissions, approximately 27% comes from building operation, and 13% comes from building material as embodied emissions (Architecture 2030 2023) In the construction industry specifically (not including the operation of buildings or assets), the majority of carbon emissions stem from the embodied carbon of materials. The building material is responsible for 82%–87% of the total upfront emissions, 6%–8% of emissions are from the transportation of building materials, and 6%–9% of emissions are due to the energy consumption of construction equipment in construction (Yan et al. 2010; Weigert et al. 2022). The use of sustainable building materials is just one of many strategies being pursued to reduce the carbon footprint of buildings (Paneru et al. 2024). Other approaches include improving the energy efficiency of buildings, adopting renewable energy sources, and implementing innovative building designs that minimize environmental impact.

Life-cycle carbon, which refers to the total amount of carbon emissions associated with a product or service throughout its entire life cycle, often is discretized into embodied carbon and operational carbon, as depicted in Fig. 2. Embodied carbon, also known as upstream carbon, refers to the carbon emissions that are associated with the production, transportation, and disposal of the materials and components that make up a product. Conversely, operational carbon, also known as downstream carbon refers to the carbon emissions associated with the use of a product, such as energy consumption during its use and maintenance. Enhanced construction techniques such as IC have the potential to decrease operational energy consumption, thereby contributing to a reduction in carbon emissions during its operational uses (Sizirici et al. 2021). However, in IC there often are additional sources of carbon emissions associated with the prefabrication of building components (e.g., emissions associated with the factory).

There is growing interest in decarbonization research within construction given the carbon footprint of the built environment.

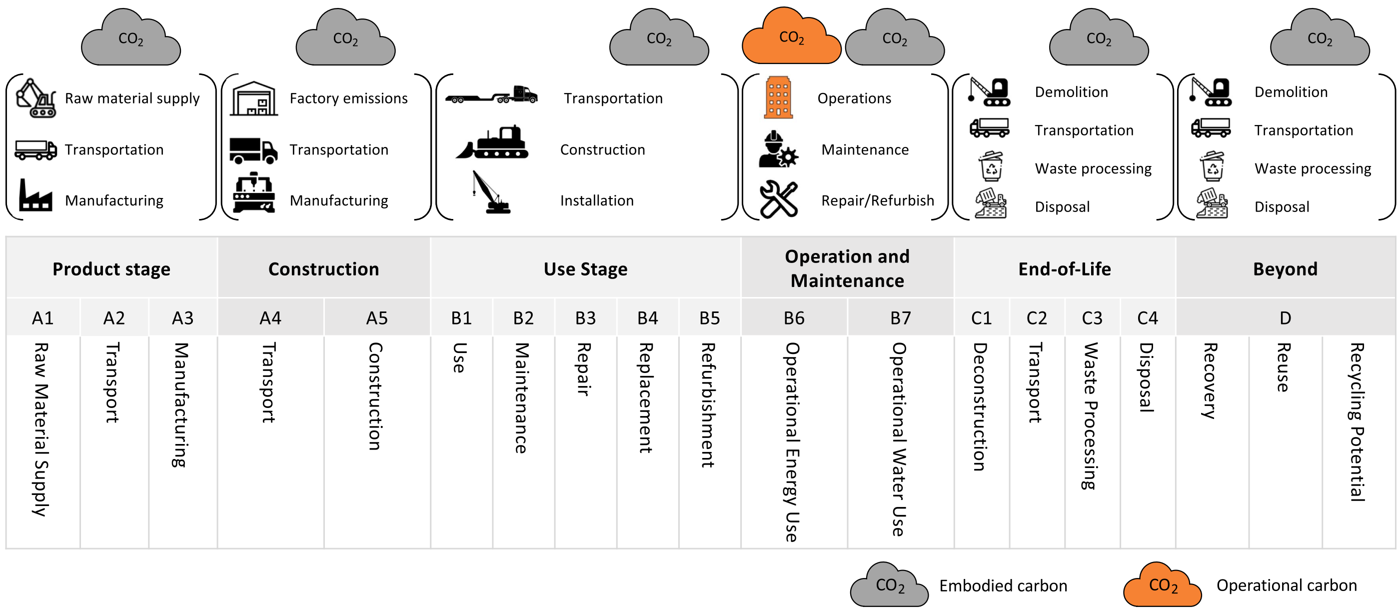

Fig. 2. Embodied carbon versus operational carbon for IC products.

Sustainable building materials such as low-carbon concrete, timber, and recycled materials are being explored to reduce environmental impacts. Traditional materials such as cement and steel emit excessive CO_2. Although countries such as the US (Plaza et al. 2020), as well as the European Union (Bjerge and Brevik 2014), have tried CO_2 capture technologies, these methods often rely heavily on resources such as fossil fuels and do not offer additional value (Chai et al. 2022). Researchers also are exploring ways to reduce emissions from the construction process, such as through the use of electric or hybrid construction equipment to minimize emissions from the installation and operation (Yan et al. 2010; Anderson 2019). In Oslo, Norway, construction at one time emitted 7% of the city's total emissions; this prompted the city to adopt extremely ambitious targets through their Climate and Energy Strategy emission-free sites by 2025 for municipal construction and by 2030 for all construction activities (Bellona 2021).

The overall carbon footprint of a building can be reduced significantly using IC practices, because the amount of waste generated in the factory typically is less than that produced on construction sites (Kedir and Hall 2021). This can help to reduce embodied carbon, because waste generated during the production of building components can be returned to the supply chain or diverted from landfills. A study in China showed that the on-site industrialization (OSI) framework is beneficial for the triple bottom line and is ideal for high-rise concrete residential buildings (Li et al. 2020). This suggests that OSI can be a new sustainable construction method. A study of a 40% assembled building in Japan found 7% carbon reduction compared with traditional cast-in-situ buildings throughout the whole life cycle (Wang et al. 2020). In addition, the overall carbon emitted during the life cycle of a building component can be reduced by more than the sum of all carbon reduced during each life-cycle phase of the building due to the better quality of products produced in an IC factory; compared with traditional methods of construction, an IC house resulted in a 34% reduction in embodied carbon (Monahan and Powell 2011). In addition, modular residential buildings located in South Korea confirmed the reduction of carbon by 36% compared with a conventional RC building (Jang et al. 2022).

Existing Studies of Decarbonization and IC

Existing reviews of IC focused on cost, schedule, and quality improvement; only a few studies have investigated a holistic approach to decarbonization research in IC. Jayawardana et al. (2023) studied the role of developed and developing economies in the environmental sustainability of IC buildings, and focused on comparing IC and its advantages in developed and developing countries. Li et al. (2022a) used mixed methods to assess the current state of sustainability of IC, and uncovered sustainability themes, research trends, and gaps. Lu et al. (2020) used a bibliometric review method, offering construction practitioners insights into strategic and technological innovations needed for green building practices. The National Renewable Energy Laboratory (NREL) has conducted novel research that focused on the decarbonization of IC and existing ways to decarbonize, e.g., emissions reduction strategies during the predevelopment and product development phases (Klammer et al. 2021); decarbonization of modular housing utilizing the sustainability benefits of mass production (Klammer et al. 2022); and the development of the Energy in Modular method to help with design, production, and delivery of affordable, net-zero-energy, low-carbon, and healthier buildings at scale by drawing synergies between design for manufacturing and assembly, process optimization, retrofit technologies, and digitization (Pless et al. 2022).

Despite the existing studies, there still is a significant gap in the literature regarding the potential of IC to contribute to decarbonization efforts in the construction industry (Table 2). Current systematic reviews are limited in addressing the decarbonization based on the BS EN 15978:2011 life-cycle phases e.g., A1–A5, B1–B7, C1–C4, and D. Some studies covering decarbonization focused on specific stages or encompassed all stages—for example, during the operations and maintenance stage (B1–B5). In addition, the NREL studies offer novel contributions aimed at enhancing the decarbonization of industrialized construction during the predevelopment phase of modular building components. The work conducted does not constitute a systematic review. However, these studies often fail to specifically highlight their focus on the prefabrication (S4) stage. Additionally, a disproportionate amount of attention has been given to the decarbonization of steel and

Table 2. Gaps with existing IC and decarbonization review approaches

Year	Review article	Research method	Theme			Life-cycle stage				
			IC	Sust	Decarb	P	C	U	E	B
2023	Jayawardana et al. (2023)	Bibliometric and qualitative review	X	X	—	X	X	—	—	—
2023	Griffiths et al. (2023)	Systematic review	—	—	X	X	X	—	X	—
2022	Li et al. (2022a)	Scientometric and systematic review	X	X[a]	—	X	X	X	—	—
2022	Kim et al. (2022)	Systematic review	—	—	X	X	X	—	X	—
2021	Qi et al. (2021)	Qualitative review	X	—	—	X	X	—	—	—
2020	Wuni et al. (2020)	Bibliometric review	X	X[a]	—	X	X	X	X	—
2020	Abdelmageed and Zayed (2020)	Bibliometric, quantitative and qualitative review	X	—	—	X	X	X	X	—
2020	Lu et al. (2020)	Bibliometric and qualitative review	—	—	X	X	X	X	—	—
2018	Teng et al. (2018)	Systematic review and meta-analysis of empirical studies	X	X[b]	—	X	X	X	X	—
2018	Jin et al. (2018)	Bibliometric and qualitative review	X	—	—	X	X	—	—	—
2016	Kamali and Hewage (2016)	Systematic review	X	—	—	X	X	X	—	—

Note: IC = industrialized construction; Sust = sustainability; Decarb = decarbonization; P = product stage, A1–A3; C = construction process stage, A4–A5; U = use stage, B1–B5; E = end-of-life stage, C1–C4; and B = beyond stage.
[a]Study investigated broad sustainability opportunities for off-site construction but did not investigate comprehensive decarbonization state of research or practice, nor did it cover the entire defined life-cycle stages in this study.
[b]Study investigated only case studies that documented comparative carbon emissions of prefabricated buildings compared with traditional base (i.e., non-prefabricated) cases, and did not capture state of research or practice for decarbonization.

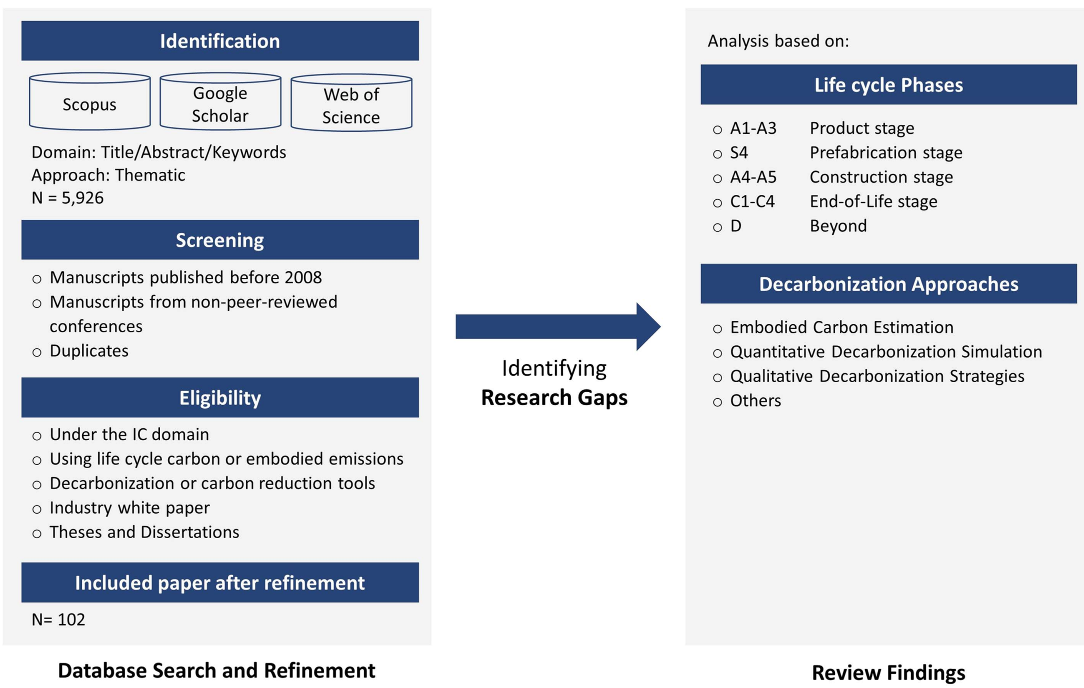

Fig. 3. Methodological framework used in this review paper.

concrete, and limited focus has been placed on mechanical, electrical, and plumbing (MEP) systems. This gap in the literature highlights the need for a holistic review of decarbonization in IC in the construction industry. Given the industry's substantial contribution to global greenhouse gas emissions, exploring ways to decarbonize IC is crucial for achieving climate goals, because IC is uniquely positioned to make a significant impact.

Review Framework

The methodological framework used in this review consisted of 3 core steps (Fig. 3):

1. Database search and refinement—Web of Science, Google Scholar, and Scopus databases were searched using criteria. Papers obtained from this search were refined using Table 3.
2. Identification of knowledge gaps—various review papers (Table 2) were reviewed to identify the existing gaps in the published scholarly works. The identified gaps also helped to focus on the review approaches to make this paper a holistic review paper.
3. Review approaches—the results were synthesized according to Life-cycle phases as suggested by EN 15978, and decarbonization approaches based on various carbon estimation and reduction strategies.

Identification

The first step in the review process was to identify relevant academic journals and databases that publish the latest developments in the field of decarbonization in construction. Journals were selected based on various parameters such as impact factor, cite

Table 3. Keywords used to identify literature sources

Category	Keyword
Decarbonization	Decarbonization* Carbon GHG Green*house CO_2 Embodied Life*cycle Emission Footprint Electrification Reus* Recycling
IC	Pre*fab* Off*site construction Off*site manufacturing Off*site fabrication OSC Modular* Paneli*ed Pre*assembly Robotic Digital fabrication Automated construction Industriali*ed

scope, Scientific Journal Rankings (SJR), and popularity in the field of decarbonization in construction. The databases of Web of Science, Google Scholar, and Scopus were used for identifying artifacts for this review. To ensure a broad range of decarbonization approaches and topics and IC methodologies, the keywords in Table 3 were used for searching across all databases. Asterisks (i.e., wildcard characters) were used to generalize common terms or subterms.

Screening and Scope

Identified publications from databases were screened for their relevance. Publications focusing on areas other than construction and decarbonization, and publications which were older than 15 years (before 2008) were excluded from the review. Therefore, publications that were selected for comprehensive review had both of the following attributes: (1) relevance to IC (as per the definition in the "Background" section); and (2) direct relevance to life-cycle carbon emissions estimation or reduction. In total, 102 artifacts from the review of the three databases met these screening criteria and were analyzed comprehensively. To accompany the screening criteria, a scope definition (Table 4) was prepared to summarize the different dimensions considered for this review. This study specifically focused on the building sector, encompasses predefined life-cycle stages [our only addition is the inclusion of a separate stage for prefabrication, building upon the work by Pan (2014)], covers all Scope 1, 2, and 3 GHG emissions, and is agnostic to material types.

Bibliometrics of Review Sources

Final review sources included journal articles, conference papers, theses, dissertations, and industry white papers to provide a multidisciplinary approach. Approximately 81% of the analysis represents journal articles, 15% conference papers, and 4% reports (industry papers) (Fig. 4).

Although the review searched for sources from 2008 and onwards, the oldest source was from 2010 and the majority of articles were from 2018 and onward (Fig. 5). Furthermore, journal articles composed the majority of source types.

Publications included in the final review also represent globally holistic approaches. The majority of sources were from China, Hong Kong, Europe, and the US (where it is likely that the practice of IC and or interest to decarbonize is more common than in other regions). In addition, sources primarily were from the residential sector, followed by the commercial sector (Fig. 6).

Review Findings

Review findings are organized into (1) life-cycle stages; and (2) decarbonization tools to cover broader aspects beyond the life-cycle assessments (LCAs). The life-cycle stages were defined based on BS EN 15978:2011, which is a standard to evaluate and report the environmental performance of buildings over the life cycle. There are five stages in the standard: A1–A3, product stage; A4–A5, construction stage; B1–B5, use stage; C1–C4, end-of-life stage; and D, beyond. In addition to the original BS EN 15978:2011 stages, Stage S4, the prefabrication stage (Pan 2014), was added between the construction stage and the use stage to incorporate the system boundary of IC buildings.

Table 4. Scope definitions used in study

Scope dimension	Defined scope element	Definition and reference (as applicable)
Industry	Building sector	The built environment generates 40% of annual global CO_2 emissions (Architecture 2030 2023)
Project phases	Product phase (A1–A3)[a], prefabrication (S4)[b], construction (A4–A5)[a], use stage (B1–B5)[a], end-of-life stage (C1–C4)[a], beyond (D)[a]	[a]From EN 15978 (British Standards Institution 2011) [b]From (Pan 2014)
Emissions type and inventory scope	Net greenhouse gas emissions, and all three carbon scopes defined by EPA	USEPA (2015)
Material types	Agnostic (i.e., all material types)	—
Literature sources	Academic (journal articles, conference papers, dissertations) and industry (white papers, reports)	—
Decarbonization topics	Decarbonization estimation and reduction tool, reduction process or method, and reduction strategy	—
Industrialization methods	Prefabrication, preassembly, off-site construction and manufacturing, digital fabrication, robotic construction, modular construction, and on-site automation	—

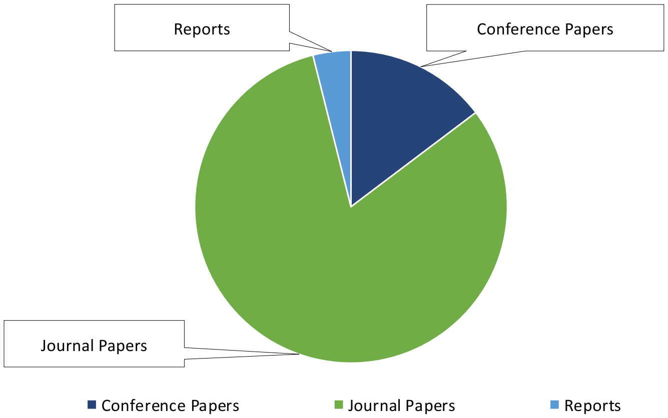

Fig. 4. Publication types for the review.

In addition to traditional life-cycle assessments, the review findings incorporated a broader range of decarbonization tools such as embodied carbon estimation, quantitative decarbonization, and qualitative decarbonization. By analyzing life-cycle stages and decarbonization, the review provides a comprehensive overview of evaluating and enhancing the decarbonization of IC beyond the conventional boundaries of life-cycle assessment.

Life-Cycle Stages

The product stage receives the most attention regarding decarbonization efforts; the use, end-of-life, and beyond stages lack sufficient study. Progress in the prefabrication and construction stages is becoming more common in recent studies, but emission tracking techniques largely are lacking. The review findings are organized based on these life-cycle stages in the following sections. Table 5 highlights the key findings.

A1–A3: Product Stage

The product stage includes three substages: raw material supply stage, transportation stage, and manufacturing stage. Over 70% of the reviewed papers specifically apply to this stage, indicating the high decarbonization potential and research interests in the stage. This stage can contribute to the decarbonization of IC through the promotion of ecofriendly materials and optimizing the transportation process.

The production of raw materials is widely known to be the biggest contributor to carbon emissions (Aghasizadeh et al. 2022).

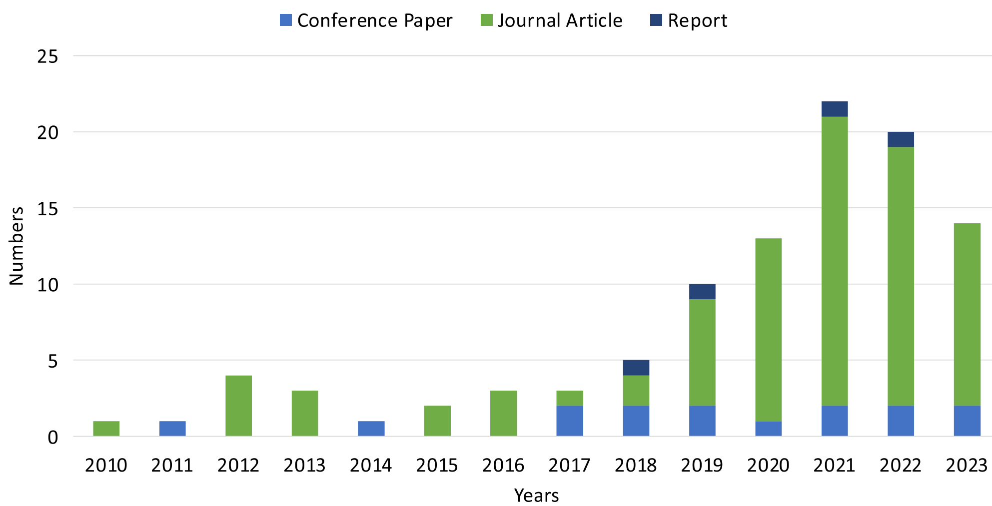

Fig. 5. Temporal distribution of reviewed publications.

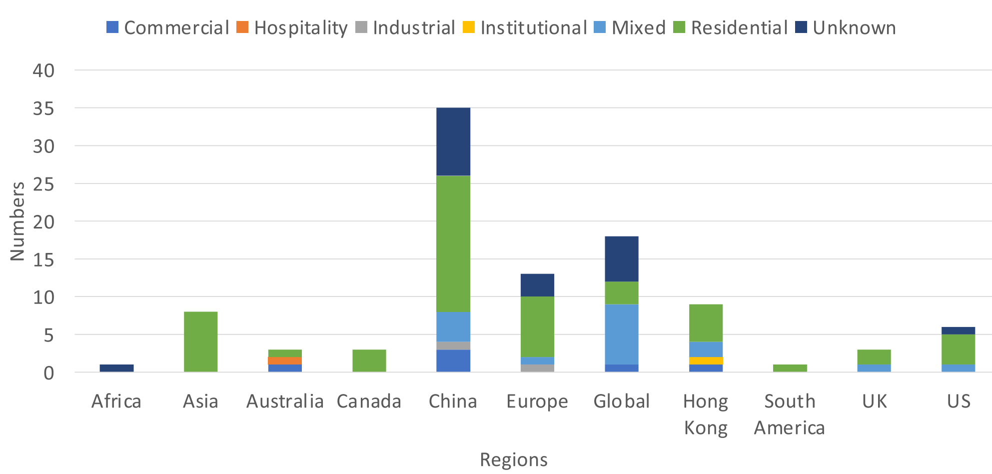

Fig. 6. Paper distribution per regions and building types.

Table 5. Summary of key findings based on life cycles

Life-cycle stages	Key findings
Product stage	• Most studied stage for decarbonization. • Essential to use low-carbon materials for reduced carbon footprint because raw materials are the largest contributor of carbon emissions. • Transportation has lower carbon emissions than raw material production, but can be more impactful when additional IC-related transportation and logistics process are added.
Prefabrication	• It is necessary to examine the appropriate level of prefabrication for decarbonization because IC does not guarantee a decrease in carbon emissions.
Construction stage	• Transportation decarbonizes by optimizing logistics in terms of vehicle type and number of shipping modules per vehicle. • Managing rework, worker transportation, labor allocation, and efficiency of assembly help reduce the carbon emissions of construction and installation process.
Use stage	• Lack of studies of stage. • Existing studies are focused on estimating carbon emissions and comparing carbon emissions of IC to those of typical buildings. • Decarbonized by increased efficiency of building operation system due to enhanced construction quality of IC.
End-of-life stage	• Lack of studies of stage. • Potential to benefit decarbonization through enabling circular economy with affordable price.
Beyond	• Lack of studies of stage. • Need for DfMA and additional technical developments to improve quality of building material recycle and reuse. • High decarbonization potential of reusing structural elements, especially cast-in-place concrete structures. • Difficulties in quantifying carbon emissions related to beyond stage.

Consequently, selecting recyclable, or low-carbon materials is key to reducing carbon footprint. For example, using timber can reduce carbon emissions by as much as 56.7% and can enhance carbon storage by 292.8% (Reyes et al. 2021). The high carbon impact of concrete needs breakthrough technologies for the reduction of emissions, such as carbon capture and storage and alternative clinkers (Favier et al. 2018). Finally, choosing low-carbon steel rebar and steel formwork can contribute to decarbonization, because steel accounts for 38% of the raw-material extraction carbon footprint in residential construction in Hong Kong (Wong and Tang 2012).

Transportation was found to be a key factor in current carbon quantification processes as its data is generally accessible and can be easily collected during the product stage (Li et al. 2021b). Although transportation often is considered to have a lower impact on carbon emissions compared to material production (Bei et al. 2021), it can become a significant source of emissions for IC due to extra plant-to-site transportation and the handling process of prefabricated modules (Pan et al. 2018; Tavares et al. 2019). In addition, as the scale and complexity of industrialization increases (Fig. 1), so does the need for addressing transportation impacts on carbon emissions. This also is the case in very dense urban regions such as Hong Kong, where transportation plays a critical role in material section and resulting carbon emissions (Teng and Pan 2019).

S4: Prefabrication

Whereas the product stage is focused on supplying and processing raw materials, the prefabrication stage involves manufacturing industrialized components or modules. Previous studies have expressed different views on the decarbonization potential of this stage. For example, Wang and Sinha (2021) concluded that the total energy and carbon footprint increases when the prefabrication rate increases. Conversely, Du et al. (2019) and Guo et al. (2023) found that the overall building carbon emissions decrease under the same condition. Hao et al. (2020) found that prefabrication saved 15% of carbon emissions because the components are manufactured in a controlled environment where less waste is generated. Considering these diverging positions, it is necessary to carefully analyze the unique attributes of a project's prefabrication levels to understand if industrialization positively or negatively contributes to the carbon emissions of a project.

A4–A5: Construction Stage

The construction stage consists of two substages: transportation, and the construction-installation process. During the transportation stage, it is important to improve the efficiency of logistics by optimizing how components are transported and by using suitable vehicles (Xiang et al. 2023). Although industrialization itself is not found to be a major source of decarbonization during the on-site construction stage (Aghasizadeh et al. 2022; Xiang et al. 2023), indirect benefits can contribute positively to reduced emissions. For example, IC decreases carbon emissions through less rework (Yuan et al. 2018), reduces worker transportation and its associated emissions (Quale et al. 2012), optimizes labor allocation (Li et al. 2017), and optimizes the efficiency of component assembly (Jang et al. 2022; Xue et al. 2023).

B1–B5: Use Stage

The use stage involves the use, maintenance, repair, replacement, and refurbishment of buildings. Most research has focused on estimating the carbon emissions of IC and comparing it with that of traditional buildings. These studies have found that IC contributes to decarbonization by controlling the construction quality, and therefore, improving the functionalities of building systems. A few studies also found potential for IC to contribute to decarbonization through design optimization (Li et al. 2021a; Shahi et al. 2021) and housing renovation energy neutrality (Decorte et al. 2020). However, the existing studies commonly indicated that the industrialized methods are not as significant as the selection and arrangement of building materials to reduce carbon emissions Still, these findings can be challenged in the future because scant research has been conducted despite the vast amount of carbon emissions generated during this long-lasting stage.

C1–C4: End-of-Life Stage

The end-of-life stage consists of four substages: deconstruction, demolition, transportation, waste processing, and disposal. Previous studies focused on the end-of-life stage for IC, especially estimating the carbon estimation during this stage and comparing it with that of traditional construction methods. Although there are only a few directly related research studies, they verified that the end-of-life stage gains decarbonization benefits through prefabrication because it enables improved logistics associated with deconstruction, transport, and waste processing (Aye et al. 2012; Tavares et al. 2021a).

D: Beyond

The beyond stage includes reuse, recovery, recycling, and potential processes. Across the reviewed publications, only 20% studied this phase. They found a significant decarbonization potential for recycling and reuse of building materials (Minunno et al. 2020; Nußholz et al. 2023; Sun et al. 2022; Tavares et al. 2021a). To enable recycling and reuse practices, DfMA and additional technical developments such as the use of bolted connections should be considered (Minunno et al. 2020; Dong et al. 2018). These techniques allow better quality of the used parts, and thus can foster the dismantling and recycling process of the building (Luna-Tintos et al. 2020). In addition, the reuse of structural elements should also be considered, especially when the reused members are oversized for structural integrity, due to its significant environmental benefits compared to the limited influence of transportation and selective deconstruction (De Wolf et al. 2018). Specifically, reusing components extracted from cast-in-place concrete structures has gained interest in Europe for this reason (Küpfer et al. 2023). In addition, there are methodological challenges in quantifying carbon emissions in the beyond stage. Currently, it is difficult to address the full spectrum of the reuse and recycling practices because quantifying critical features such as embedded use value, versatility, storage, and transformation impacts is difficult (De Wolf et al. 2020). Moreover, it is unclear if the reused components should inherit the environmental impact of the materials' initial life (Kuzmenko et al. 2021).

Decarbonization Tools and Approaches

This section presents a comprehensive review of the tools and strategies suggested in previous studies to facilitate the decarbonization potential of IC. The decarbonization approaches have been categorized into the following four subsections: (1) embodied carbon estimation, (2) quantitative decarbonization simulations, (3) qualitative decarbonization strategies, and (4) other categories. These topics are discussed in the following subsections, providing explanations and insights from prior research. Table 6 highlights the key findings.

Embodied Carbon Estimation

One of the most significant research topics in the decarbonization of IC is the precise measurement of carbon emissions for projects. This subsection contains studies that focused on accurately quantifying the embedded carbon produced associated with the production and use of a product. To quantify such embedded carbon, many studies examined specific building cases and proposed frameworks to accurately calculate the carbon emissions generated during the projects. Recommendations for low-carbon pathways often are addressed to structural designers by developing, establishing, and validating a transparent, quantifiable, and consistent assessment approach to estimate the embodied life-cycle impacts of building structures (Chen et al. 2022; Pan et al. 2018). Tailored models are proposed to estimate embedded carbon, considering the specific characteristics and patterns of carbon release at different project stages.

In this process, the critical aspect is determining at which stage of the project to measure carbon emissions. Due to the distinctive carbon release patterns in each of these stages, several models tailored to estimate embedded carbon using various phase cut-off methods have been proposed. Life-cycle emissions encompass all the greenhouse gas emissions generated from the initial extraction of raw materials to the final disposal of a product. As previously

Table 6. Summary of key findings based on decarbonization tools and approaches

Current research area	Key findings
Embodied carbon estimation	• Proposing assessment frameworks for accurate carbon emission calculations. • Determining the appropriate project stage for measurement is crucial due to the distinctive emission patterns for each stage. • Most studies primarily focused on estimating carbon emissions for A1–A5, product and construction stages.
Quantitative decarbonization simulation	• Discussion for various methods for reducing carbon emissions, which were verified through simulations. • Circular building strategies, including reuse and recycling, demonstrate significant potential for decarbonization. • Replacing traditional construction methods with prefabrication shows the potential for decarbonization.
Qualitative decarbonization strategies and policies	• Expanding the range of carbon reduction tools (including software solutions, process enhancements, and educational resources). • Potential within the construction value chain. • Adapting BIM for carbon efficiency. • Adapting strategies from other industries. • Discussions of policy and project-level strategies remain theoretical without quantitative measurements.
Other	• Examination of sustainability status of industrial construction in the individual country level. • Comparison of decarbonization impact between traditional methods and industrial construction.

defined, the life-cycle stages of a construction project are categorized into the product stage (A1–A3), construction stage (A4–A5), use stage (B1–B5), end-of-life stage (C1–C4), and beyond (D). Most of the studies estimating embodied carbon focused on the product stage and construction stage within A1–A5 (Xue et al. 2023; Xu et al. 2022). For example, life-cycle assessment was carried out for the manufacturing and transportation of prefabrication elements during the production, taking into account all the background information, such as raw material extraction, manufacturing, and transport (cradle to site) (Wong and Tang 2012). In addition to the construction phase, the operation and maintenance (O&M) phase also has a significant impact on carbon emissions during the whole life-cycle. Pless et al. (2022) proposed a calculating model including the O&M phase (B5). Lim et al. (2017) and Teng and Pan (2019) proposed carbon quantitative models that consider the entire building cycle from Stage A1 to Stage C4. For example, Teng and Pan (2019) proposed a probabilistic model that can estimate carbon emissions during the construction process, even with incomplete data, such as estimated data or temporal conditions. The model achieves this by combining the data quality index method with the Monte Carlo simulation procedure. Using research that integrates the entire life cycle into the carbon emission calculation process, the model can recognize key factors of carbon emissions during industrialized construction projects.

Quantitative Decarbonization Simulation

In addition to studies proposing a system for precise embodied carbon estimation, various approaches have been introduced to implement diverse construction management methods and models aimed at mitigating carbon emissions. This section comprises studies that aimed to quantitatively verify the effectiveness of those approaches through simulations. The process of decarbonization calculation or estimation entails precisely quantifying the amount of carbon emissions that necessitate reduction to attain specific decarbonization objectives. Within these simulation studies, explicit carbon reduction methods and target values are proposed, and their efficacy is supported by evidence derived from emission simulations.

For example, Reyes et al. (2021) conducted a simulation study that compared the decarbonization impact of a building-as-usual scenario with an optimistic scenario employing prefabricated timber structures. The findings revealed that although the increased adoption of timber construction, particularly for buildings between one and six stories, led to a reduction in emissions ranging from 1% to 11%, it did not suffice to achieve carbon neutrality. However, it did demonstrate a significant potential for CO_2 storage within the building structures (Reyes et al. 2021).

Moreover, the implementation of circular building strategies, which incorporate elements such as reuse, durability, disassembly, and recycling, has demonstrated substantial potential for decarbonization across various types of construction projects, including new builds, renovations, and demolitions. For instance, a study conducted in Xi'an City in China showed if the single traditional cast-in-situ method is adopted, the total carbon emission is expected to reach 68.21 million tons in 2030. Under the active implementation of the prefabricated construction policy, it is expected that by 2030, using prefabricated buildings to replace traditional cast-in-situ buildings can reduce emissions by 12.56 million tons (Tian et al. 2022). Many of these simulation studies proposed and validated carbon reduction targets quantitatively. However, simulation studies heavily rely on input data for accurate modeling, and research outcomes based on specific country and project type data may face challenges in generalization. In this regard, there is need for research considering the applicability to a wider range of construction projects.

Qualitative Decarbonization Strategies or Policies

In this third category, the focus is on studies exploring a diverse array of tools and strategies designed to facilitate carbon reduction. A carbon reduction tool encompasses both digital and physical components; some studies focus on the development of software-based solutions, whereas others explore proposals for enhancing work processes to minimize carbon emissions. These tools can include software applications that track carbon emissions, physical products that promote energy efficiency or renewable energy, or educational resources that help individuals and organizations reduce their carbon footprint. Additionally, some studies investigated the application of tangible materials to achieve effective carbon reduction strategies. A combination of breakthrough technologies, efficient use, and recycling of material, structural optimism and circular economy principles, and so forth augment the carbon reduction goals. A study conducted in China used on-site industrialization that combines the advantages of prefabrication and cast-in-situ principles. This framework includes five basic industrialized principles: standardization, prefabrication, modularization, lean, and sustainability (Li et al. 2020). Digital tools such as building information modeling (BIM) also are helpful in assisting with life-cycle analysis (Paneru et al. 2021; Yevu et al. 2023). In IC projects, Zhang et al. (2016) showed that BIM can support the work during the modular design and installation phase to achieve decarbonization. BIM integration with Design for manufacturing and assembly principles can result in further reduction of emissions (Abd Razak et al. 2022). Furthermore, some studies aimed to develop low-carbon strategies by adapting carbon reduction approaches from other industries to the realm of IC projects (Honic et al. 2019). Among these approaches, the implementation of a material passport—an established circular economy tool in the manufacturing industry—was explored for its potential to reduce carbon emissions throughout the entire life cycle of building projects. Notably, Atta et al. (2021) put forth a plan to apply material passports to prefabricated buildings, effectively utilizing them to mitigate carbon emissions during the construction phase. Policy-level strategies or project-level management processes aimed at reducing carbon emissions also have been discussed (Du et al. 2021; Liu et al. 2022). Many studies in this category remain theoretical and lack quantitative measurements of carbon emissions. However, they highlight the importance of comprehensive approaches to carbon reduction, fostering a broader understanding of systemic change requirements.

Other

Studies that fall outside the three other categories are presented here, focusing on guiding the future direction of decarbonization in IC. Although these studies may not introduce specific tools, strategies, or frameworks, they offer valuable insights for advancing IC low carbonization. Among these studies, some explored the sustainability status of IC, with reference to the current state of individual countries. Jayawardana et al. (2023) conducted a comparative analysis of IC sustainability in developing and developed countries, whereas Attouri et al. (2022) examined the current state of IC in France and highlighted the benefits of its sustainability. Additionally, researchers reviewed the sustainability potential of various IC submethods, such as prefabricated construction and modular construction (Li and Zhang 2022; Hu and Chong 2019). Most studies in this category comparatively observed the decarbonization impact between existing construction methods and IC methods. Instead of proposing specific tools or strategic directions, these studies focused on understanding the extent to which the IC method contributes to low carbonization compared to conventional construction methods. A prominent area of investigation is studying the factors responsible for differences in carbon emissions between existing buildings and IC buildings (Zhou et al. 2023; Tavares et al. 2021b) Furthermore, Dong et al. (2015) compared the carbon content of concrete materials between the traditional cast-in-situ method and the precast method for private high-rise buildings. Jang et al. (2022) compared the relationship between construction cost and carbon emissions in conventional construction methods and IC.

Challenges

The challenges facing the decarbonization potential of IC can be delineated into three discrete categories (Fig. 7): (1) challenges associated with successful IC practice; (2) challenges associated with decarbonization methodologies and their use in construction; and (3) unique challenges inherent to an IC approach for achieving decarbonization.

The first group of challenges is based on the ability to achieve a successful IC project (in terms of time, cost, and quality), irrespective of specific considerations related to decarbonization. For example, if improper project performance leads to the creation of waste (in this case related to material waste, but also process waste), not only does this cause cost and schedule overruns, it also impacts the ability to achieve specific decarbonization goals. Based on our review of the literature, we found that up-front costs associated with implementing IC practices and approaches, supply chain variability, and fragmentation (Kedir et al. 2023; Pless et al. 2022; Dong et al. 2015), and regional regulations, prescriptive codes, and incentive schemes (Jayawardana et al. 2023; Wang et al. 2022) are other challenges associated with successful decarbonization in IC practices. These challenges impede the overall success of an IC project, impacting not only cost, time, and quality but also decarbonization, because they can amount to additional embodied and operational emissions within IC projects.

The challenges associated with carbon estimation methodologies are the second category identified in the literature. These challenges relate to choices, assumptions, and processes used to estimate, track, and evaluate carbon emissions during the up-front design and planning stage. The following challenges exist across all forms of construction, both for IC and non-IC projects. However, we include this category here because in order to understand the true decarbonization potential of IC, it is necessary to have transparent and accurate carbon estimation—something which still is difficult to achieve. Key challenges when estimating emissions for IC is the lack of consensus about whether prefabrication should be considered as part of A3 or A5 in the current LCA framework (Xue et al. 2023; Pan et al. 2020; Teng and Pan 2020; Pan et al. 2019), the difficulty of maintaining accurate material databases for common materials used in construction (either IC or non-IC) (Li et al. 2021b, 2022b, 2023; Zhao et al. 2023; Yevu et al. 2023; Chen et al. 2022; Hao et al. 2020), the manual effort often required to estimate accurate carbon data for a given building (Xu et al. 2022; Chen et al. 2022), and assumptions about the payback period for LCA evaluation, including assumptions surrounding end-of-life reuse and recovery (Xu and Liu 2021; Minunno et al. 2020; Decorte et al. 2020; Pan et al. 2019; Agustí-Juan et al. 2019; Aye et al. 2012).

Finally, there are additional challenges that are unique to IC which are not based on the overall successful execution of the project nor on the verbosity of carbon estimation methodologies. These challenges include the additional materials which are required to facilitate transport and craning (Greer and Horvath 2023; Gislason et al. 2022; Bertram et al. 2023; Teng et al. 2018), the fact that the majority of emissions may not stem from IC activities (Gislason et al. 2022) and instead could stem from upstream raw material extraction and manufacturing (Sun et al. 2022; Jang et al. 2022; Aghasizadeh et al. 2022; Liu et al. 2022), or from the operations phase of building (Bonamente and

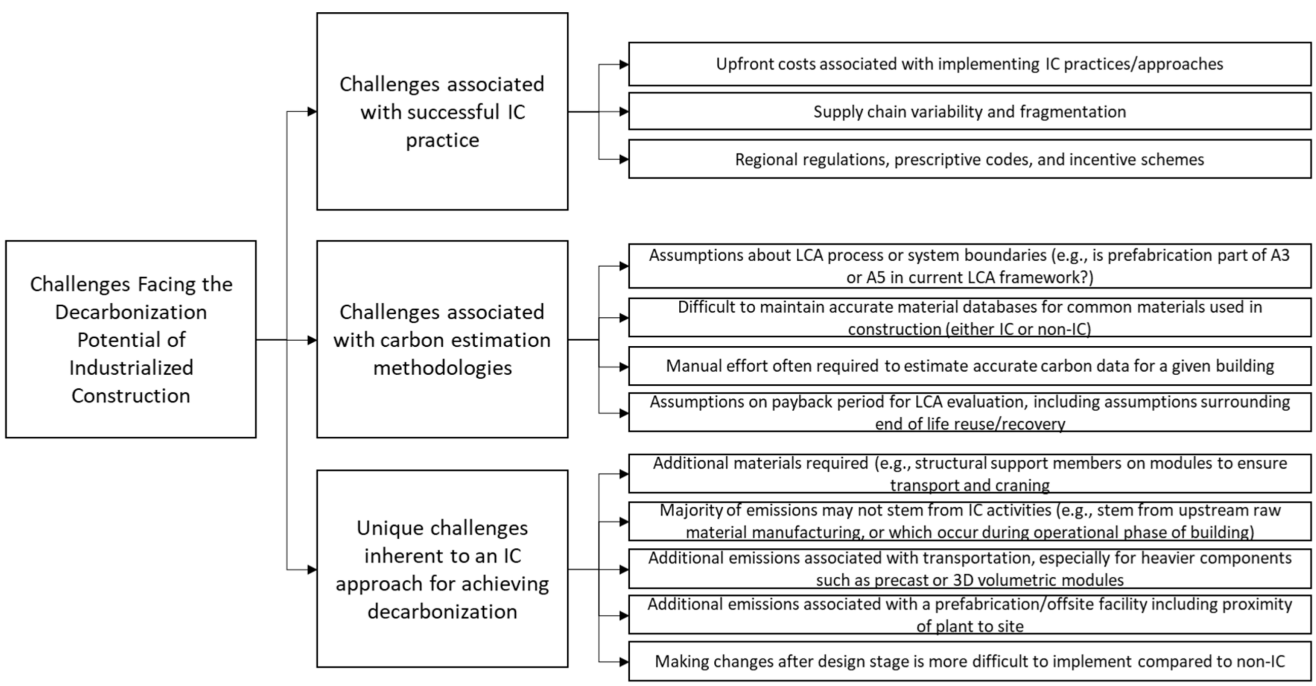

Fig. 7. Summary of the challenges facing the decarbonization potential of IC.

Cotana 2015). Similarly, there may be additional emissions associated with transportation, especially for heavier components such as precast or 3D volumetric modules (Tavares et al. 2019; Pan et al. 2018; Teng et al. 2018; Kamali and Hewage 2016; Mao et al. 2013); additional emissions associated with a prefabrication or off-site facility, including the proximity of the plant to the site (Wang and Sinha 2021; Qiao et al. 2018); and that fact that making changes after design stage is more difficult to implement in IC than in non-IC projects (Li et al. 2021a). Collectively, these challenges often result in net additional carbon emissions inherent in the way that IC is executed, which must be considered as part of the overall net decarbonization potential of a project.

Discussion

The decarbonization potential afforded by IC offers significant opportunities to enhance the environmental performance of buildings. However, current research primarily focuses on estimating carbon emissions, neglecting other crucial aspects such as carbon reduction processes or strategies. There is a lack of established systematic analysis methods to quantitatively assess the potential of carbon emissions reduction through IC techniques, possibly due to the varying effects of different building types on carbon emissions (Hao et al. 2020). For example, although some studies propose carbon reduction measures for IC buildings, they often fail to estimate the actual reduction potential (Chen et al. 2022). Moreover, the calculation methods used in these studies often rely on traditional carbon emission factor (CEF) approaches, which might overlook essential details specific to industrialized buildings (Xue et al. 2023). There also is a lack of research comparing carbon emissions between IC buildings and traditional cast-in-situ buildings (Zhou et al. 2023). Additionally, limited studies have compared the environmental impacts of constructing single-family houses using different construction methods (Kamali et al. 2019).

Previous cradle-to-grave life-cycle assessments have not adequately quantified and balanced the costs and environmental tradeoffs between IC and conventional construction methods (Tavares et al. 2021b). To optimize both carbon emissions and costs, there is a clear need for dual-objective optimization (Guo et al. 2023). However, the integration of lean practices and the use of IC methods have received less attention (Heravi et al. 2020). Furthermore, incorporating cultural and climate factors can significantly enhance the adaptability of IC (Du et al. 2021). An opportunity lies in exploring the combined approach of reuse and recycling and understanding their differential impacts on environmental metrics, such as material savings and greenhouse gas emissions reduction (Minunno et al. 2020). Leveraging a circular economy can maximize economic benefits by efficiently managing materials through the three steps of reduce, reuse, and recycle (Aghasizadeh et al. 2022).

Despite the potential benefits, only a few studies have investigated the extent and trends of the impact of varying degrees of IC. For example, it remains unclear whether the carbon-reducing effect increases with the degree of industrialization (Du et al. 2019; Tavares et al. 2021a). Previous reviews of IC building sustainability have been too generic and provided limited insights into research progress (Wuni et al. 2020). One of the issues is the inconsistent definition of life-cycle stages (product, construction, operation, and so forth) for different levels of industrialization (component, assembly, 2D panelized, 3D volumetric, and so forth), resulting in verbose carbon footprint results (Xu et al. 2022). Additionally, standard environmental assessment methods need to be adapted for digital fabrication processes to adequately capture their environmental impact.

Across IC research, a significant focus has been directed toward reducing carbon emissions during project phases (A1–A3) (Li et al. 2021b), and limited attention has been given to transportation-related emissions (Tavares et al. 2019). Evaluating carbon emission reduction effects from the construction supply chain perspective remains a challenge (Sun et al. 2022), and previous studies have found different contributions of transportation to embodied carbon emissions (Xiang et al. 2023). Additionally, there is a lack of real-time analysis in the operation phase (B6-B7), hindering effective carbon emission control during the operational phase (Liu et al. 2020).

A research gap is evident because previous studies primarily focused on on-site construction activities and neglected broader community environmental impacts, considering the large domain covered by industrialized processes. Systematic and quantitative assessments of environmental impacts specific to industrialized buildings are lacking (Yao et al. 2020). Non-greenhouse gas emissions in off-site construction have not been studied conclusively (Sandanayake et al. 2019), and there is a lack of standard phases for carbon emissions and measurement methods for similar IC buildings (Ding et al. 2020).

Comparative analysis revealed that IC timber has the lowest life-cycle impacts among concrete, steel, and timber IC school buildings (Koronaki et al. 2021). Existing tools for building performance assessment have limitations in real-time evaluation and visualization, restricting their use in early design phases (Agustí-Juan et al. 2018). Uncertainty in input parameters and analytical models has been overlooked in some studies of embodied carbon in IC high-rise buildings, leading to potential misinterpretation of results (Teng and Pan 2020).

The calculation results of carbon emissions in previous IC building life-cycle assessments may be biased and therefore sufficient confidence in these results may be lacking (Kong et al. 2020; Pan et al. 2019). This highlights the need for a phasewise carbon tracking mechanism to address these issues.

Future Research Directions

There is a pressing need to establish standardized life-cycle assessments for IC buildings based on the climatic zones, especially in areas where space heating and cooling demands are higher. These assessments should be conducted at the component levels, considering carbon emissions associated with labor (human activities) when comparing conventional construction (IC) with nonconventional methods (Teng et al. 2018). Additionally, it is crucial to explore alternative materials within IC that can significantly reduce carbon emissions from fuels and raw materials (Zhou et al. 2023).

When studying carbon emissions, it is essential to factor in all the building components. For example, it is essential to account for the emissions generated from the insulation of cast-in-place and precast components (Guo et al. 2023). Likewise, in the context of IC buildings, comprehensive studies are needed to assess carbon emissions at various spatial levels with consistent system boundaries (Xu et al. 2022). Developing a universally recognized boundary definition for quantifying embodied carbon should be a vital research goal (Chen et al. 2022). To better understand the relationship between assembly rate and carbon emissions, investigations should be conducted (Li et al. 2021b, 2022b; Hao et al. 2020; Tavares et al. 2019; Wang and Sinha 2021). Moreover, optimizing the operational carbon impact of equipment (Qiao et al. 2018), evaluating emissions from construction equipment during panel unloading and installation (Lee et al. 2022), and accurately estimating carbon emissions from vehicles (Ding et al. 2020) require further research. Future studies should assess the benefits of strategies aimed at reducing carbon specifically by exploring the marketability of reused building components and end-of-life management, as well as investigating the economic and social aspects of implementing circular economy practices, which are important avenues for research (Minunno et al. 2020).

The continuous emission monitoring system can be expanded to include radio-frequency identification (RFID) tags for tracking carbon emissions from IC components. Monitoring and comparing carbon emissions at various stages of IC also can be achieved using RFID (Liu et al. 2020). Integrating life-cycle assessment into BIM software can help simulate embodied, operational, and end-of-life impacts and costs, enabling non-LCA experts to assess buildings' impact during the design stage. These databases should allow easy updates to respond to regional and temporal variability (Tavares et al. 2021a).

The development and application of new carbon emission factors are necessary to track emissions from IC buildings (Zhao et al. 2023). Creating regionally representative databases related to IC processes for ease of component shifting also is a crucial research avenue to pursue (Jayawardana et al. 2023).

Technological applications such as BIM, DfMA, lean construction, and sustainability play a significant role in IC research trends. Future research could explore areas such as generative design, cloud data exchange, and 3D printing (Qi et al. 2021). It is essential to develop novel approaches that prioritize low-carbon end-of-life recycling and reuse, avoiding energy-intensive processes such as 3D printing (Agustí-Juan et al. 2018). Investigating the dynamic impact of technological progress on abatement costs and the effectiveness of various low-carbon practices is another important direction (Wang et al. 2022).

Establishing a comprehensive quantitative assessment framework for IC to track sustainability is essential (Li et al. 2022a). Moreover, incorporating parameters that affect IC optimization (Li et al. 2021a), and exploring materials such as nanotechnology are crucial for reducing the carbon emissions of IC components (Kong et al. 2020). Table 7 highlights the key challenges and opportunities identified from the review.

Conclusion

The construction sector is a significant contributor to global CO_2 emissions and is pivotally positioned to influence the decarbonization of global value chains if it is executed in a systematic approach. IC is a promising approach for mitigating both embodied and operational emissions, which is attributed to its streamlined approach to resource efficiency, vertically integrated supply chains, enhanced quality, and controlled production environments. However, the efficacy of these reductions is contingent on the scale, complexity, and successful execution of well-planned IC methods. To ensure that IC projects achieve their full carbon reduction potential, it is important to carefully consider the entire life-cycle of the product, from the choice of materials to the end-of-life management. Moreover, the emissions generated by a building project span various phases including product manufacturing, construction, operations, maintenance, and eventual decommissioning; however, due to gaps in the current carbon assessment methodologies, the carbon documenting process can be very difficult. This challenge is accentuated by challenges and accelerators such as a fragmented supply chain, lack of skilled labor, and geographic location that determines the sources of energy.

The technologies related to IC, including computer vision, artificial intelligence, digital fabrication, and so forth, are propelling the architecture, engineering, and construction (AEC) industry forward in terms of quality, sustainability, and scalability. Although numerous studies allude to the various sustainability attributes of IC, no studies to date present a thorough, comprehensive review of the decarbonization potential of IC from a life-cycle standpoint. Such a review is necessary because, without a detailed understanding of the ways that IC can provide decarbonization benefits (including current opportunities and challenges), the industry may be prone to relying on broad assumptions about the decarbonization potential of IC instead of specific and data-driven lessons learned for how to best achieve decarbonization. This paper provides a comprehensive review of the existing literature that documents the decarbonization potential of IC, reporting findings according to life-cycle stages and according to key decarbonization themes.

This review found that the vast majority of current research is focused on the estimation of carbon emissions in product stages A1–A3; however, actual carbon tracking throughout IC projects is missing. The validation of emissions is critical for accurate, transparent, and comprehensive assessments in the future. More research needs to study construction stages A4–A5 to identify the emissions contribution at construction sites and to monitor and understand the contribution from assembly processes of IC components. The end-of-life stages C1–C4 and the beyond stage D also need further study concerning decarbonization potential.

Overall, this review found that conflicting perspectives pervade the existing literature regarding the true and specific decarbonization potential of IC. Although the majority of research infers that IC

Table 7. Summary of key research gaps identified from the review

Thematic area	Research gaps
Successful IC practice	• Lack of established methods to quantitatively assess the potential of carbon emissions specific to IC component • Lack of research comparing carbon emissions between IC buildings and traditional cast-in-situ buildings • Emissions from scale and complexity of ICs
Current decarbonization methods and their use in construction	• Development of carbon emissions factor catering to regional needs • Generative design, cloud data exchange, and 3D printing • Explorations of new materials
IC practice and approach for achieving decarbonization	• Carbon tracking to validate simulation results • Carbon emissions with respect to change in degree of IC practices • System boundary definition to quantify embodied carbon

has great potential for decarbonization, select studies found that the emissions reduction may not be so significant. To elaborate further on the conflicting evidence in the literature regarding the true decarbonization afforded by IC, it is important to understand the role that current challenges play. This review found three unique types of challenges for achieving decarbonization in IC. The first set of challenges relates to the successful project execution of IC (a challenge that predominately impacts the cost, schedule, and quality performance of IC). The second set of challenges involves the ambiguity and verbosity of the current carbon estimation methodologies, which include numerous variables and uncertainties (in addition, IC has specific deviations from conventional construction projects, which further compound the challenge of estimating carbon emissions). Finally, IC has unique challenges for decarbonization based on the additional materials, transportation, and on-site process which introduce additional embodied emissions compared with non-IC (conventional) construction projects.

The authors highlight the following limitations of this study, which potentially may impact the overall findings. First, we provided a detailed review of the academic literature. The purpose of this study was to identify key lessons learned for the IC industry. However, because the academic literature provides a robust overview of the state of the IC industry (in particular, several white paper studies conducted by a leading national laboratory), the authors are confident that the key challenges, opportunities, and future research areas align with findings and feedback from industry professionals. Furthermore, several of the authors have worked within the IC industry, which provides a unique perspective on the industry translation of findings made in this study. The other limitation is the scope and breadth of the search process employed. Although the authors attempted to capture all relevant keywords related to IC and decarbonization, there is a possibility that alternate keywords were missed, resulting in relevant studies not being considered.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

References

Abdelmageed, S., and T. Zayed. 2020. "A study of literature in modular integrated construction—Critical review and future directions." *J. Cleaner Prod.* 277 (Jun): 124044. https://doi.org/10.1016/j.jclepro.2020.124044.

Abd Razak, M. I., M. A. Khoiry, W. H. Wan Badaruzzaman, and A. H. Hussain. 2022. "DfMA for a better industrialised building system." *Buildings* 12 (6): 794. https://doi.org/10.3390/buildings12060794.

Aghasizadeh, S., A. Tabadkani, A. Hajirasouli, and S. Banihashemi. 2022. "Environmental and economic performance of prefabricated construction: A review." *Environ. Impact Assess. Rev.* 97 (Jan): 106897. https://doi.org/10.1016/j.eiar.2022.106897.

Agustí-Juan, I., A. Hollberg, and G. Habert. 2018. "Early-design integration of environmental criteria for digital fabrication." In *Proc., 6th Int. Symp. on Life-Cycle Civil Engineering (IALCCE 2018, Life Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision)*. Boca Raton, FL: CRC Press.

Agustí-Juan, I., A. Jipa, and G. Habert. 2019. "Environmental assessment of multi-functional building elements constructed with digital fabrication techniques." *Int. J. Life Cycle Assess.* 24 (6): 1027–1039. https://doi.org/10.1007/s11367-018-1563-4.

Anderson, J. E. 2019. *Zero emission zero waste construction sites in California commercial construction: A case study.* San Luis Obispo, CA: DigitalCommons@CalPoly.

Architecture 2030. 2023. "Why the building sector?" Accessed March 16, 2023. https://architecture2030.org/why-the-building-sector/.

Atta, I., E. S. Bakhoum, and M. M. Marzouk. 2021. "Digitizing material passport for sustainable construction projects using BIM." *J. Build. Eng.* 43 (Apr): 103233. https://doi.org/10.1016/j.jobe.2021.103233.

Attouri, E., Z. Lafhaj, L. Ducoulombier, and B. Linéatte. 2022. "The current use of industrialized construction techniques in France: Benefits, limits and future expectations." *Cleaner Eng. Technol.* 7 (Feb): 100436. https://doi.org/10.1016/j.clet.2022.100436.

Aye, L., T. Ngo, R. H. Crawford, R. Gammampila, and P. Mendis. 2012. "Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules." *Energy Build.* 47 (Jan): 159–168. https://doi.org/10.1016/j.enbuild.2011.11.049.

Bei, J., Z. Huang, and Y. Chang. 2021. "Carbon-dioxide mitigation of prefabricated residential buildings in China: An urbanization-based estimation." In *Proc., 2021 5th Int. Conf. on Vision, Image and Signal Processing*. New York: IEEE. https://doi.org/10.1109/ICVISP54630.2021.00034.

Bellona. 2021. "Norwegian cities lead the way in reaching zero-emissions in construction sites." Accessed April 8, 2023. https://bellona.org/news/zecs/2021-03-norwegian-cities-lead-the-way-in-reaching-zero-emissions-in-construction-sites.

Bertram, N., S. Fuchs, J. Mischke, R. Palter, G. Strube, and J. Woetzel. 2023. *Modular construction: From projects to products*. New York: McKinsey.

Bjerge, L.-M., and P. Brevik. 2014. "CO_2 capture in the cement industry, Norcem CO_2 capture project (Norway)." *Int. J. Greenhouse Gas Control* 63 (Sep): 6455–6463. hhttps://doi.org/10.1016/J.EGYPRO.2014.11.680.

Bonamente, E., and F. Cotana. 2015. "Carbon and energy footprints of prefabricated industrial buildings: A systematic life cycle assessment analysis." *Energies* 8 (11): 12685–12701. https://doi.org/10.3390/en81112333.

British Standards Institution. 2011. "BS EN 15978:2011 Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method." Accessed July 18, 2023. https://www.en-standard.eu/bs-en-15978-2011-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/.

Chai, S. Y. W., L. H. Ngu, B. S. How, M. Y. Chin, K. Abdouka, M. J. B. A. Adini, and A. M. Kassim. 2022. "Review of CO_2 capture in construction-related industry and their utilization." *Int. J. Greenhouse Gas Control* 119 (Sep): 103727. https://doi.org/10.1016/j.ijggc.2022.103727.

Chen, Y., Y. Zhou, W. Feng, Y. Fang, and A. Feng. 2022. "Factors that influence the quantification of the embodied carbon emission of prefabricated buildings: A systematic review, meta-analysis and the way forward." *Buildings* 12 (8): 1265. https://doi.org/10.3390/buildings12081265.

Decorte, Y., M. Steeman, U. B. Krämer, C. Struck, K. Lange, B. Zander, and A. de Haan. 2020. "Upscaling the housing renovation market through far-reaching industrialization." *IOP Conf. Ser.: Earth Environ. Sci.* 588 (3): 032041. https://doi.org/10.1088/1755-1315/588/3/032041.

De Wolf, C., E. Hoxha, and C. Fivet. 2020. "Comparison of environmental assessment methods when reusing building components: A case study." *Sustainable Cities Soc.* 61 (Sep): 102322. https://doi.org/10.1016/j.scs.2020.102322.

De Wolf, C. E. L., J. Brütting, and C. Fivet. 2018. "Embodied carbon benefits of reusing structural components in the built environment: A medium-rise office building case study." In *Proc., PLEA 2018 Conf.* Lausanne, Switzerland: EPFL Publication.

Ding, Z., S. Liu, L. Luo, and L. Liao. 2020. "A building information modeling-based carbon emission measurement system for prefabricated residential buildings during the materialization phase." *J. Cleaner Prod.* 264 (Feb): 121728. https://doi.org/10.1016/j.jclepro.2020.121728.

Dong, L., Y. Wang, H. X. Li, B. Jiang, and M. Al-Hussein. 2018. "Carbon reduction measures-based LCA of prefabricated temporary housing with renewable energy systems.” *Sustainability* 10 (3): 718. https://doi.org/10.3390/su10030718.

Dong, Y., L. Jaillon, P. Chu, and C. S. Poon. 2015. “Comparing carbon emissions of precast and cast-in-situ construction methods—A case study of high-rise private building.” *Constr. Build. Mater.* 99 (Aug): 39–53. https://doi.org/10.1016/j.conbuildmat.2015.08.145.

Du, Q., T. Bao, Y. Li, Y. Huang, and L. Shao. 2019. “Impact of prefabrication technology on the cradle-to-site CO_2 emissions of residential buildings.” *Clean Technol. Environ. Policy* 21 (7): 1499–1514. https://doi.org/10.1007/s10098-019-01723-y.

Du, Q., Q. Pang, T. Bao, X. Guo, and Y. Deng. 2021. “Critical factors influencing carbon emissions of prefabricated building supply chains in China.” *J. Cleaner Prod.* 280 (Sep): 124398. https://doi.org/10.1016/j.jclepro.2020.124398.

European Commission. 2003. “*Climate action 2050 long-term strategy*.” Accessed February 21, 2023. https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en.

Favier, A., C. De Wolf, K. Scrivener, and G. Habert. 2018. *A sustainable future for the European cement and concrete industry: Technology assessment for full decarbonisation of the industry by 2050*. Rep. Zurich, Switzerland: ETH Zurich.

Gislason, S., S. Bruhn, L. Breseghello, B. Sen, G. Liu, and R. Naboni. 2022. “Porous 3D printed concrete beams show an environmental promise: A cradle-to-grave comparative life cycle assessment.” *Clean Technol. Environ. Policy* 24 (8): 2639–2654. https://doi.org/10.1007/s10098-022-02343-9.

Greer, F., and A. Horvath. 2023. “Modular construction’s capacity to reduce embodied carbon emissions in California’s housing sector.” *Build. Environ.* 240 (Jun): 110432. https://doi.org/10.1016/j.buildenv.2023.110432.

Griffiths, S., B. K. Sovacool, D. D. Furszyfer Del Rio, A. M. Foley, M. D. Bazilian, J. Kim, and J. M. Uratani. 2023. “Decarbonizing the cement and concrete industry: A systematic review of socio-technical systems, technological innovations, and policy options.” *Renewable Sustainable Energy Rev.* 180 (Apr): 113291. https://doi.org/10.1016/j.rser.2023.113291.

Guo, F., Y. Zhang, C. Chang, and Y. Yu. 2023. “Carbon emissions of assembly buildings constrained by flexible resource: A study on cost optimization.” *Buildings* 13 (1): 90. https://doi.org/10.3390/buildings13010090.

Hao, J. L., B. Cheng, W. Lu, J. Xu, J. Wang, W. Bu, and Z. Guo. 2020. “Carbon emission reduction in prefabrication construction during materialization stage: A BIM-based life-cycle assessment approach.” *Sci. Total Environ.* 723 (Feb): 137870. https://doi.org/10.1016/j.scitotenv.2020.137870.

Hatami, M., S. Paneru, and I. Flood. 2022. *Applicability of artificial intelligence (AI) methods to construction manufacturing: A literature review*, 1298–1306. Reston, VA: ASCE. https://doi.org/10.1061/9780784483961.136.

Heravi, G., M. Rostami, and M. F. Kebria. 2020. “Energy consumption and carbon emissions assessment of integrated production and erection of buildings’ pre-fabricated steel frames using lean techniques.” *J. Cleaner Prod.* 253 (Apr): 120045. https://doi.org/10.1016/j.jclepro.2020.120045.

Honic, M., I. Kovacic, and H. Rechberger. 2019. “Assessment of the recycling potential and environmental impact of building materials using material passports—A case study.” In *Energy efficient building design and legislation (2019)*, 172–179. Champs-sur-Marne, France: RILEM Publications S.A.R.L.

Hu, X., and H.-Y. Chong. 2019. “Environmental sustainability of off-site manufacturing: A literature review.” *Eng. Constr. Archit. Manage.* 28 (1): 332–350. https://doi.org/10.1108/ECAM-06-2019-0288.

Huang, L., G. Krigsvoll, F. Johansen, Y. Liu, and X. Zhang. 2018. “Carbon emission of global construction sector.” *Renewable Sustainable Energy Rev.* 81 (Jan): 1906–1916. https://doi.org/10.1016/j.rser.2017.06.001.

Jang, H., Y. Ahn, and S. Roh. 2022. “Comparison of the embodied carbon emissions and direct construction costs for modular and conventional residential buildings in South Korea.” *Buildings* 12 (1): 51. https://doi.org/10.3390/buildings12010051.

Jayawardana, J., A. K. Kulatunga, J. A. S. C. Jayasinghe, M. Sandanayake, and G. Zhang. 2023. “Environmental sustainability of off-site construction in developed and developing regions: A systematic review.” *J. Archit. Eng.* 29 (2): 04023008. https://doi.org/10.1061/JAEIED.AEENG-1420.

Jin, R., S. Gao, A. Cheshmehzangi, and E. Aboagye-Nimo. 2018. “A holistic review of off-site construction literature published between 2008 and 2018.” *J. Cleaner Prod.* 202 (Jun): 1202–1219. https://doi.org/10.1016/j.jclepro.2018.08.195.

Kamali, M., and K. Hewage. 2016. “Life cycle performance of modular buildings: A critical review.” *Renewable Sustainable Energy Rev.* 62 (Jun): 1171–1183. https://doi.org/10.1016/j.rser.2016.05.031.

Kamali, M., K. Hewage, and R. Sadiq. 2019. “Conventional versus modular construction methods: A comparative cradle-to-gate LCA for residential buildings.” *Energy Build.* 204 (Sep): 109479. https://doi.org/10.1016/j.enbuild.2019.109479.

Kamar, K., Z. A. Hamid, M. Azman, and M. Ahamad. 2011. “Industrialized building system (IBS): Revisiting issues of definition and classification.” *Int. J. Emerging Sci.* 1 (2): 120.

Kazem-Zadeh, M., and R. R. A. Issa. 2020. *Constraints of modular construction for fully serviced and finished homes: Lessons learned from Canada*, 1057–1063. Reston, VA: ASCE. https://doi.org/10.1061/9780784482889.112.

Kedir, F., and D. M. Hall. 2021. “Resource efficiency in industrialized housing construction—A systematic review of current performance and future opportunities.” *J. Cleaner Prod.* 286 (Apr): 125443. https://doi.org/10.1016/j.jclepro.2020.125443.

Kedir, F., D. M. Hall, D. Ioannidou, T. Rupper, R. Boyd, and A. Hollberg. 2023. “Resource efficiency in industrialised construction: A study in developing economies.” *Proc. Inst. Civ. Eng. Eng. Sustainability* 176 (2): 94–105. https://doi.org/10.1680/jensu.22.00048.

Kim, J., B. K. Sovacool, M. Bazilian, S. Griffiths, J. Lee, M. Yang, and J. Lee. 2022. “Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options.” *Energy Res. Social Sci.* 89 (Jun): 102565. https://doi.org/10.1016/j.erss.2022.102565.

Klammer, N., Z. Kaufman, A. Podder, S. Pless, D. Celano, and S. Rothgeb. 2021. *Decarbonization during predevelopment of modular building solutions*. Rep. No. NREL/TP-5500-81037. Golden, CO: National Renewable Energy Lab. https://doi.org/10.2172/1837021.

Klammer, N., Z. Kaufman, A. Podder, S. Pless, D. Celano, and S. Rothgeb. 2022. *A life cycle decarbonization of modular building solutions*. Rep. No. NREL/CP-5500-83606. Golden, CO: National Renewable Energy Lab.

Kong, A., H. Kang, S. He, N. Li, and W. Wang. 2020. “Study on the carbon emissions in the whole construction process of prefabricated floor slab.” *Appl. Sci.* 10 (7): 2326. https://doi.org/10.3390/app10072326.

Koronaki, A., A. Bukauskas, A. Jalia, D. U. Shah, and M. H. Ramage. 2021. “Prefabricated engineered timber schools in the United Kingdom: Challenges and opportunities.” *Sustainability* 13 (22): 12864. https://doi.org/10.3390/su132212864.

Küpfer, C., M. Bastien-Masse, and C. Fivet. 2023. “Reuse of concrete components in new construction projects: Critical review of 77 circular precedents.” *J. Cleaner Prod.* 383 (Sep): 135235. https://doi.org/10.1016/j.jclepro.2022.135235.

Kuzmenko, K., C. Roux, A. Feraille, and O. Baverel. 2021. “Assessing environmental impact of digital fabrication and reuse of constructive systems.” *Structures* 31 (Jun): 1300–1310. https://doi.org/10.1016/j.istruc.2020.05.035.

Larsson, J., P. E. Eriksson, T. Olofsson, and P. Simonsson. 2014. “Industrialized construction in the Swedish infrastructure sector: Core elements and barriers.” *Construct. Manage. Econ.* 32 (1–2): 83–96. https://doi.org/10.1080/01446193.2013.833666.

Lee, Y., S. Chin, and M. Fischer. 2022. *Impacts of stacking plans on carbon emissions during transportation of prefabricated exterior wall panels*, 1136–1143. Reston, VA: ASCE. https://doi.org/10.1061/9780784483893.139.

Li, H. X., L. Zhang, D. Mah, and H. Yu. 2017. “An integrated simulation and optimization approach for reducing CO_2 emissions from on-site construction process in cold regions.” *Energy Build.* 138 (Jun): 666–675. https://doi.org/10.1016/j.enbuild.2016.12.030.

Li, L., Z. Li, X. Li, S. Zhang, and X. Luo. 2020. “A new framework of industrialized construction in China: Towards on-site industrialization.” *J. Cleaner Prod.* 244 (Sep): 118469. https://doi.org/10.1016/j.jclepro.2019.118469.

Li, L., H. Luan, X. Yin, Y. Dou, M. Yuan, and Z. Li. 2022a. “Understanding sustainability in off-site construction management: State of the art and future directions.” *J. Constr. Eng. Manage.* 148 (11): 03122008. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002396.

Li, S., Y. Cui, N. Banaitienė, C. Liu, and M. B. Luther. 2021a. “Sensitivity analysis for carbon emissions of prefabricated residential buildings with window design elements.” *Energies* 14 (19): 6436. https://doi.org/10.3390/en14196436.

Li, X., W. Xie, L. Xu, L. Li, C. Y. Jim, and T. Wei. 2022b. “Holistic life-cycle accounting of carbon emissions of prefabricated buildings using LCA and BIM.” *Energy Build.* 266 (Sep): 112136. https://doi.org/10.1016/j.enbuild.2022.112136.

Li, X., W. Xie, T. Yang, C. Lin, and C. Y. Jim. 2023. “Carbon emission evaluation of prefabricated concrete composite plates during the building materialization stage.” *Build. Environ.* 232 (Aug): 110045. https://doi.org/10.1016/j.buildenv.2023.110045.

Li, X.-J., J. Lai, C. Ma, and C. Wang. 2021b. “Using BIM to research carbon footprint during the materialization phase of prefabricated concrete buildings: A China study.” *J. Cleaner Prod.* 279 (Sep): 123454. https://doi.org/10.1016/j.jclepro.2020.123454.

Li, Y., and J. Zhang. 2022. *An empirical study on energy saving and emissions reduction of prefabricated buildings based on the whole life cycle*, 69–78. Reston, VA: ASCE. https://doi.org/10.1061/9780784484562.008.

Lim, P. Y., K. Yahya, E. Aminudin, R. Zakaria, Z. Haron, R. M. Zin, and A. A. H. Redzuan. 2017. “Carbon footprint of construction using industrialised building system.” *IOP Conf. Ser.: Mater. Sci. Eng.* 271 (1): 012107. https://doi.org/10.1088/1757-899X/271/1/012107.

Liu, C., Y. Song, R. Li, W. Ma, J. L. Hao, and G. Qiang. 2023. “Three-level modular grid system for sustainable construction of industrialized residential buildings: A case study in China.” *J. Cleaner Prod.* 395 (Jun): 136379. https://doi.org/10.1016/j.jclepro.2023.136379.

Liu, G., R. Chen, P. Xu, Y. Fu, C. Mao, and J. Hong. 2020. “Real-time carbon emission monitoring in prefabricated construction.” *Autom. Constr.* 110 (Feb): 102945. https://doi.org/10.1016/j.autcon.2019.102945.

Liu, G., R. Huang, K. Li, A. Shrestha, and X. Fu. 2022. “Greenhouse gas emissions management in prefabrication and modular construction based on earned value management.” *J. Constr. Eng. Manage.* 148 (6): 04022034. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002268.

Lowe, T. 2002. “Modular construction emits 45% less carbon than traditional methods, report finds.” Accessed April 1, 2023. https://www.building.co.uk/news/modular-construction-emits-45-less-carbon-than-traditional-methods-report-finds/5117779.article.

Lu, W., V. W. Y. Tam, H. Chen, and L. Du. 2020. “A holistic review of research on carbon emissions of green building construction industry.” *Eng. Constr. Archit. Manage.* 27 (5): 1065–1092. https://doi.org/10.1108/ECAM-06-2019-0283.

Luna-Tintos, J. F., C. Cobreros, Á. López-Escamilla, R. Herrera-Limones, and M. Torres-García. 2020. “Methodology to evaluate the embodied primary energy and CO_2 production at each stage of the life cycle of prefabricated structural systems: The case of the solar decathlon competition.” *Energies* 13 (17): 4311. https://doi.org/10.3390/en13174311.

Mao, C., Q. Shen, L. Shen, and L. Tang. 2013. “Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects.” *Energy Build.* 66 (Feb): 165–176. https://doi.org/10.1016/j.enbuild.2013.07.033.

Minunno, R., T. O’Grady, G. M. Morrison, and R. L. Gruner. 2020. “Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building.” *Resour. Conserv. Recycl.* 160 (Jul): 104855. https://doi.org/10.1016/j.resconrec.2020.104855.

Monahan, J., and J. C. Powell. 2011. “An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework.” *Energy Build.* 43 (1): 179–188. https://doi.org/10.1016/j.enbuild.2010.09.005.

Nußholz, J., S. Çetin, L. Eberhardt, C. De Wolf, and N. Bocken. 2023. “From circular strategies to actions: 65 European circular building cases and their decarbonisation potential.” *Resour. Conserv. Recycl. Adv.* 17 (Aug): 200130. https://doi.org/10.1016/j.rcradv.2023.200130.

Pan, W. 2014. “System boundaries of zero carbon buildings.” *Renewable Sustainable Energy Rev.* 37 (Aug): 424–434. https://doi.org/10.1016/j.rser.2014.05.015.

Pan, W., A. G. F. Gibb, and A. R. J. Dainty. 2008. “Leading UK housebuilders’ utilization of offsite construction methods.” *Build. Res. Inf.* 36 (1): 56–67. https://doi.org/10.1080/09613210701204013.

Pan, W., K. Iturralde, T. Bock, R. G. Martinez, O. M. Juez, and P. Finocchiaro. 2020. “A conceptual design of an integrated façade system to reduce embodied energy in residential buildings.” *Sustainability* 12 (14): 5730. https://doi.org/10.3390/su12145730.

Pan, W., K. Li, and Y. Teng. 2019. “Briefing: Life-cycle carbon assessment of prefabricated buildings: Challenges and solutions.” *Proc. Inst. Civ. Eng. Eng. Sustainability* 172 (1): 3–8. https://doi.org/10.1680/jensu.17.00063.

Pan, W., Y. Teng, K. Li, and C. Yu. 2018. *Implications of prefabrication for the life cycle carbon emissions of high-rise buildings in high-density urban environment*, 493–502. Reston, VA: ASCE. https://doi.org/10.1061/9780784481301.049.

Paneru, S., F. Foroutan Jahromi, M. Hatami, W. Roudebush, and I. Jeelani. 2021. “Integration of emergy analysis with building information modeling.” *Sustainability* 13 (14): 7990. https://doi.org/10.3390/su13147990.

Paneru, S., P. Ghimire, A. Kandel, S. Kafle, and C. Rausch. 2024. “Embodied residential building carbon emissions reduction in Nepal using linear optimization modeling.” *J. Build. Eng.* 84 (May): 108531. https://doi.org/10.1016/j.jobe.2024.108531.

Plaza, M. G., S. Martínez, and F. Rubiera. 2020. “CO_2 capture, use, and storage in the cement industry: State of the art and expectations.” *Energies* 13 (21): 5692. https://doi.org/10.3390/en13215692.

Pless, S., et al. 2022. *The energy in modular (EMOD) buildings method: A guide to energy-efficient design for industrialized construction of modular buildings*. Rep. No. NREL/TP-5500-82447. Golden, CO: National Renewable Energy Lab. https://doi.org/10.2172/1875070.

Qi, B., M. Razkenari, A. Costin, C. Kibert, and M. Fu. 2021. “A systematic review of emerging technologies in industrialized construction.” *J. Build. Eng.* 39 (Aug): 102265. https://doi.org/10.1016/j.jobe.2021.102265.

Qiao, C., P. Hu, and J. Gao. 2018. “Study on carbon emission of in-plant transportation in the components’ production stage of prefabricated building.” *IOP Conf. Ser.: Earth Environ. Sci.* 199 (3): 032077. https://doi.org/10.1088/1755-1315/199/3/032077.

Quale, J., M. J. Eckelman, K. W. Williams, G. Sloditskie, and J. B. Zimmerman. 2012 “Construction matters: Comparing environmental impacts of building modular and conventional homes in the United States.” *J. Ind. Ecol.* 16 (2): 243–253. https://doi.org/10.1111/j.1530-9290.2011.00424.x.

Rahman, M., and H. R. Sobuz. 2018. “Comparative study of IPS & PPVC precast system—A case study of public housing buildings project in Singapore.” In *Proc., 4th Int. Conf. on Civil Engineering for Sustainable Development (ICCESD 2018)*, 9–11. Khulna, Bangladesh: Khulna Univ. of Engineering and Technology.

Reyes, N., et al. 2021. “Achieving zero carbon emissions in the construction sector: The role of timber in decarbonising building structures.” In *Cambridge open engage*. Cambridge, UK: Cambridge University Press. https://doi.org/10.33774/coe-2021-hgd6q-v2.

Sandanayake, M., W. Luo, and G. Zhang. 2019. “Direct and indirect impact assessment in off-site construction—A case study in China.” *Sustainable Cities Soc.* 48 (Sep): 101520. https://doi.org/10.1016/j.scs.2019.101520.

Shahi, S., P. Wozniczka, C. Rausch, I. Trudeau, and C. Haas. 2021. “A computational methodology for generating modular design options

J. Constr. Eng. Manage., 2024, 150(9): 03124005

for building extensions." *Autom. Constr.* 127 (Jun): 103700. https://doi.org/10.1016/j.autcon.2021.103700.

Sharifi, A., and Y. Yamagata. 2016. "Principles and criteria for assessing urban energy resilience: A literature review." *Renewable Sustainable Energy Rev.* 60 (Sep): 1654–1677. https://doi.org/10.1016/j.rser.2016.03.028.

Sizirici, B., Y. Fseha, C. S. Cho, I. Yildiz, and Y. J. Byon. 2021. "A review of carbon footprint reduction in construction industry, from design to operation." *Materials* 14 (20): 6094. https://doi.org/10.3390/ma14206094.

Song, J., W. R. Fagerlund, C. T. Haas, C. B. Tatum, and J. A. Vanegas. 2005. "Considering prework on industrial projects." *J. Constr. Eng. Manage.* 131 (6): 723–733. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:6(723).

Sun, S., Y. Chen, A. Wang, and X. Liu. 2022. "An evaluation model of carbon emission reduction effect of prefabricated buildings based on cloud model from the perspective of construction supply chain." *Buildings* 12 (10): 1534. https://doi.org/10.3390/buildings12101534.

Tavares, V., J. Gregory, R. Kirchain, and F. Freire. 2021a. "What is the potential for prefabricated buildings to decrease costs and contribute to meeting EU environmental targets?" *Build. Environ.* 206 (Aug): 108382. https://doi.org/10.1016/j.buildenv.2021.108382.

Tavares, V., N. Lacerda, and F. Freire. 2019. "Embodied energy and greenhouse gas emissions analysis of a prefabricated modular house: The 'Moby' case study." *J. Cleaner Prod.* 212 (Apr): 1044–1053. https://doi.org/10.1016/j.jclepro.2018.12.028.

Tavares, V., N. Soares, N. Raposo, P. Marques, and F. Freire. 2021b. "Prefabricated versus conventional construction: Comparing life-cycle impacts of alternative structural materials." *J. Build. Eng.* 41 (Sep): 102705. https://doi.org/10.1016/j.jobe.2021.102705.

Teng, Y., K. Li, W. Pan, and T. Ng. 2018. "Reducing building life cycle carbon emissions through prefabrication: Evidence from and gaps in empirical studies." *Build. Environ.* 132 (Jan): 125–136. https://doi.org/10.1016/j.buildenv.2018.01.026.

Teng, Y., and W. Pan. 2019. "Systematic embodied carbon assessment and reduction of prefabricated high-rise public residential buildings in Hong Kong." *J. Cleaner Prod.* 238 (Feb): 117791. https://doi.org/10.1016/j.jclepro.2019.117791.

Teng, Y., and W. Pan. 2020. "Estimating and minimizing embodied carbon of prefabricated high-rise residential buildings considering parameter, scenario and model uncertainties." *Build. Environ.* 180 (Jan): 106951. https://doi.org/10.1016/j.buildenv.2020.106951.

Tian, L., R. Jiang, X. Chen, J. Xie, L. Wang, X. Liu, and J. Dang. 2022. "Emission reduction prediction and policy simulation of prefabricated buildings using system dynamics." In Vol. 14620 of *Proc., Int. Conf. on Smart Transportation and City Engineering (STCE 2022)*, 328–334. Bellingham, WA: SPIE. https://doi.org/10.1117/12.2658301.

USEPA. 2015. "Overview of greenhouse gases." Accessed March 2, 2023. https://www.epa.gov/ghgemissions/overview-greenhouse-gases.

Wang, H., Y. Zhang, W. Gao, and S. Kuroki. 2020. "Life cycle environmental and cost performance of prefabricated buildings." *Sustainability* 12 (7): 2609. https://doi.org/10.3390/su12072609.

Wang, S., and R. Sinha. 2021. "Life cycle assessment of different prefabricated rates for building construction." *Buildings* 11 (11): 552. https://doi.org/10.3390/buildings11110552.

Wang, X., Q. Du, C. Lu, and J. Li. 2022. "Exploration in carbon emission reduction effect of low-carbon practices in prefabricated building supply chain." *J. Cleaner Prod.* 368 (Apr): 133153. https://doi.org/10.1016/j.jclepro.2022.133153.

Weigert, M., O. Melnyk, L. Winkler, and J. Raab. 2022. "Carbon emissions of construction processes on urban construction sites." *Sustainability* 14 (19): 12947. https://doi.org/10.3390/su141912947.

Wong, F., and Y. T. Tang. 2012. "Comparative embodied carbon analysis of the prefabrication elements compared with in-situ elements in residential building development of Hong Kong." *Int. J. Civ. Environ. Eng.* 6 (2): 89–94. https://doi.org/10.5281/ZENODO.1080574.

Wuni, I. Y., G. Q. Shen, and R. Osei-Kyei. 2020. "Sustainability of off-site construction: A bibliometric review and visualized analysis of trending topics and themes." *J. Green Build.* 15 (4): 131–154. https://doi.org/10.3992/jgb.15.4.131.

Xiang, Y., K. Ma, A.-M. Mahamadu, L. Florez-Perez, K. Zhu, and Y. Wu. 2023. "Embodied carbon determination in the transportation stage of prefabricated constructions: A micro-level model using the bin-packing algorithm and modal analysis model." *Energy Build.* 279 (Sep): 112640. https://doi.org/10.1016/j.enbuild.2022.112640.

Xu, J., Y. Teng, W. Pan, and Y. Zhang. 2022. "BIM-integrated LCA to automate embodied carbon assessment of prefabricated buildings." *J. Cleaner Prod.* 374 (Jun): 133894. https://doi.org/10.1016/j.jclepro.2022.133894.

Xu, M., and Y. Liu. 2021. "Environmental impact assessment of Materialization Stage of prefabricated buildings based on LCA and WTP." *IOP Conf. Ser.: Earth Environ. Sci.* 634 (1): 012020. https://doi.org/10.1088/1755-1315/634/1/012020.

Xue, L., C.-R. Li, and Y.-M. Jin. 2023. "An improved carbon emission calculation framework of precast concrete column in construction stage based on LCA." *J. Chin. Inst. Eng.* 46 (3): 220–228. https://doi.org/10.1080/02533839.2023.2170924.

Yan, H., Q. Shen, L. C. H. Fan, Y. Wang, and L. Zhang. 2010. "Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong." *Build. Environ.* 45 (4): 949–955. https://doi.org/10.1016/j.buildenv.2009.09.014.

Yao, F., G. Liu, Y. Ji, W. Tong, X. Du, K. Li, A. Shrestha, and I. Martek. 2020. "Evaluating the environmental impact of construction within the industrialized building process: A monetization and building information modelling approach." *Int. J. Environ. Res. Public Health* 17 (22): 8396. https://doi.org/10.3390/ijerph17228396.

Yevu, S. K., E. K. Owusu, A. P. C. Chan, K. Oti-Sarpong, I. Y. Wuni, and M. O. Tetteh. 2023. "Systematic review on the integration of building information modelling and prefabrication construction for low-carbon building delivery." *Build. Res. Inf.* 51 (3): 279–300. https://doi.org/10.1080/09613218.2022.2131504.

Yuan, Z., C. Sun, and Y. Wang. 2018. "Design for manufacture and assembly-oriented parametric design of prefabricated buildings." *Autom. Constr.* 88 (Apr): 13–22. https://doi.org/10.1016/j.autcon.2017.12.021.

Zhang, J., Y. Long, S. Lv, and Y. Xiang. 2016. "BIM-enabled modular and industrialized construction in China." *Procedia Eng.* 145 (Jun): 1456–1461. https://doi.org/10.1016/j.proeng.2016.04.183.

Zhang, X. Q. 2016. "The trends, promises and challenges of urbanisation in the world." *Habitat Int.* 54 (Nov): 241–252. https://doi.org/10.1016/j.habitatint.2015.11.018.

Zhao, Y., L. Liu, and M. Yu. 2023. "Comparison and analysis of carbon emissions of traditional, prefabricated, and green material buildings in materialization stage." *J. Cleaner Prod.* 406 (Apr): 137152. https://doi.org/10.1016/j.jclepro.2023.137152.

Zhou, F., Y. Ning, X. Guo, and S. Guo. 2023. "Analyze differences in carbon emissions from traditional and prefabricated buildings combining the life cycle." *Buildings* 13 (4): 874. https://doi.org/10.3390/buildings13040874.