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Role of Modularity in Adoption of Offsite Construction

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Offsite construction is beneficial for cost and schedule savings, creating a safer construction environment, and sustainability. Despite its historical use in the US since 1908, offsite construction has faced challenges in gaining a significant market share. Recently renewed interest has emerged, driven by increased housing demand and labor shortages. Leveraging prior research, this paper categorizes drivers from existing literature and investigates how modularization enhances these factors. A systematic literature review reveals that modularity can significantly benefits drivers of offsite construction grouped under different categories such as: cost and profitability, schedule, safety and quality, environmental sustainability, design and engineering and adoption of new technologies. The systematic literature review was followed by interviews with subject matter experts. The interviews highlighted the importance of modularity for efficiency and profitability, suggesting its potential to drive increased adoption in the industry.

Key Words: offsite construction, modular construction, modularity, modularization, prefabrication.

Introduction

The US construction industry faces inefficiencies, prompting the exploration of offsite construction as a promising strategy to address challenges such as schedule delays, cost overruns, and safety concerns. Offsite construction involves fabricating building elements in a controlled environment and transporting them to the site for assembly. It offers advantages like cost and time reductions, decreased defects and waste, and improved environmental and safety outcomes (Karthik et al., 2020; Peng & Kim, 2022; Bhattacharjee et al., 2016). Jaillon and Poon (2008) emphasized reduced site disturbance, highlighting improved safety, and minimized disruptions. Another emerging technology of additive manufacturing in construction is being researched for its benefits. The benefits of this technology include freedom of design, customization, and the ability to create complex structures. However, drawbacks such as high cost, limited application in large structures, and issues with mass production (Ngo et al., 2018). These issues are making it less attractive compared to offsite construction.

The practice of offsite construction is not new in the United States, with historical examples such as Sears' Modern Homes program from 1908 to 1940 (Cooke & Friedman, 2001). Despite documented advantages, it has not been consistently used in the US due to concerns about perceived freedom of design and aesthetics. However, with increasing housing demand, labor shortages, and the emergence of BIM, there is a renewed interest in offsite construction. Recent research underscores the usefulness of offsite construction in increasing affordability and sustainability, especially in the multi-family construction sector. Despite the demand for affordable housing and evident positive impacts, offsite construction's adoption in the US remains at 6.03% in 2022 (Modular Building Institute, 2022).

Amidst the pressing issue of inadequate affordable housing, particularly affecting minority populations in the US, the Department of Housing and Urban Development (HUD) has strategically aimed to address this concern by promoting the use of offsite construction methods. In alignment with this objective, HUD (2023) has undertaken a comprehensive study to identify gaps in existing offsite construction research and outline potential research directions, categorizing them into six main domains (shown in Figure 1). While these domains are exclusive from each other, the authors hypothesize that dimensional standardization, referred to as modularization in this study, holds the potential to positively impact all six domains.

Modularity involves standardizing dimensions to create a versatile unit by forming a production platform to meet industry needs (Rupnik et al., 2022). As standardization is important in manufacturing it is relevant to making offsite construction viable (Crowley, 1998). The incorporation of modularity can enhance the capabilities of offsite construction (Tan et al., 2023). This paper explores, *how modularity can influence the adoption of offsite construction*? Leveraging prior research, the study categorizes drivers into eight areas and aims to understand the extent to which modularization can enhance these drivers. This methodological choice builds upon existing studies, providing a comprehensive understanding of the interplay between modularization and the drivers of offsite construction (Rupnik et al., 2022; HUD, 2023).

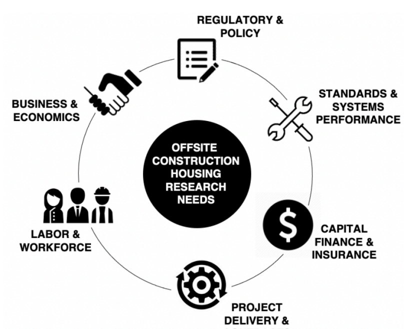

Figure 1: Major domains of research to increase adoption of offsite construction (HUD, 2023)

For this study, a two-part approach was employed. Initially, a systematic literature review was undertaken, followed by interviews with subject matter experts. The following sections present an outline of the literature review's findings, elaborate on the interview process, and conclude by summarizing the inferences from interviews. This exploratory study is a part of an ongoing project and at the time of preparing this manuscript, four interviews have been completed.

Method

For the systematic literature review, academic databases such as American Society of Civil Engineers (ASCE) and Taylor and Francis (T&F) were used. Research publications were included if they had "modular construction" and "offsite construction" in the title and abstract. This was based on the assumption that authors would naturally include these terms when their articles focused on or were related to offsite construction. Using these search criteria and including articles published from 2015 onwards, and excluding articles that were not related to construction, a total of 83 articles were identified for this review. By synthesizing and refining the existing knowledge on drivers, the study explored how modularization, as a strategy contributes to the drivers that propel the adoption of offsite construction.

The subsequent phase of the study comprised semi-structured interviews with industry professionals possessing extensive experience in offsite construction in the US. The recruitment of participants was executed through the professional networking platform LinkedIn, a widely recognized platform for industry networking and connection. The interviews were transcribed and analyzed which provided perspectives from industry experts about the role of modularity in the adoption of offsite construction.

Findings

To understand the themes in the existing literature, the gathered articles were categorized using a two-fold approach: first, the articles were categorized based on their primary focus, and subsequently, they were categorized according to the specific research methodologies employed. Nearly one-third of the articles emphasized on the use of technologies in offsite construction, followed by risk management and project scheduling. Approximately 10% of the articles explored offsite construction with 'Industry 4.0,' sustainability, lean practices, AI, and robotics. Healthcare and residential sectors were predominant with the use of offsite, but modularity's role in offsite construction lacked representation. The following sections discuss how modularity impacts the identified drivers.

Impact of Modularity on Cost and Profitability

In this section, the authors have presented a summary of the articles that have discussed the use of modularity to enhance drivers of offsite construction within the “cost and profitability” category (Table 1). The efficacy of any strategy hinges on cost considerations and profitability. When considering the adoption of offsite construction, critical cost factors include labor, transportation, design and engineering, onsite assembly, and material procurement. Additionally, factors like initial capital, speed of return on investment, scalability of the economy, and financial risk play integral roles. Notably, the incorporation of modularization results in significant labor savings, potentially reducing construction time by 50%–60% (Ding et al., 2022). Modularization, as adopted by a few Swedish manufacturers and highlighted in the HUD report (2023), addresses these challenges, offering predictability and cost savings (O’Connor et al., 2015). Effective onsite assembly requires skilled labor, module sequencing, and module standardization. Modularization leverages a learning curve benefit during assembly (O’Connor et al., 2015). The Mckinsey (2017) report underscores the importance of standardization, modularization, and lean philosophies for enhanced productivity in design and engineering.

High initial capital costs pose a significant barrier to offsite construction (Abdul Nabi & El-Adaway, 2022). Despite motivating factors, such as proven manufacturing techniques in the factory environment, no positive impact on initial capital costs has been established through modularization (O’Connor et al., 2016). The extended return on investment cycle is associated with higher initial capital costs. While studies show modularization benefits, there are cost disadvantages, including expenses for market assessment and design standards development (O’Connor et al., 2016). The scalability of the economy and financial risk factors are crucial aspects that need further exploration in studies on impact of modularity.

Table 1

Impact of modularity on drivers within “Cost and Profitability “category

	Drivers	Positive effect of Modularity	Citations
Cost and Profitability	Labor costs	✓	Ding et al., 2022
	Overhead costs	✓	Ding et al., 2022
	Supervision costs	✓	Ding et al., 2022
	Transportation costs*		
	Initial (capital) costs		Abdul Nabi & El-adaway, 2022 Jayawardana et al., 2023; Karthik et al., 2020; O’Connor et al., 2015; Zhu et al., 2021
	Installation and assembly costs	✓	O’Connor et al., 2015
	Crane and equipment costs	✓	O’Connor et al., 2015
	Design and engineering costs		
	Material costs	✓	O’Connor et al., 2015
	Speed of return on investment and profitability		
	Economy of scale		
	Management	✓	Eldamnhoury & Hanna, 2020
	Risks and Financing		
	Planning and processes	✓	Eldamnhoury & Hanna, 2020
	Supply chain and procurement		Li et al., 2022; O’Connor et al., 2015

* Mentioned by the interviewee as a possible impact of modularity

Impact of Modularity on Schedule

In this section, the authors have provided an overview of articles discussing the application of modularity to enhance drivers of offsite construction within the "schedule" category (Table 2). Schedule-related drivers for offsite construction include activity sequencing, site disruption delays due to climate dependency, design engineering lead time, transportation lead time, and commissioning and testing. Sequencing can be enhanced by adding skilled labor to the factory, monitoring onsite construction standards before module installation, and minimizing on-site trades (Pan et al., 2023). Some pre-assembly in a facility allows for logical sequencing and predefined processes, minimizing delays due to climatic factors (Lerche et al., 2020). However, the impact of modularity on sequencing was not found in the reviewed articles.

Allocating sufficient lead time and early design freeze are identified strategies to minimize disputes (Abdul Nabi & El-adaway, 2022). Standardized modules bring predictability and may reduce the lead time required for engineering and manufacturing. However, as mentioned in HUD (2021), U.S. transportation permits are regulated on a state level, making lead times for interstate transport still unpredictable, especially for oversized modules. This challenge can be addressed by adopting modularity to develop smaller reconfigurable modules, limiting the assembly size, and minimizing interstate transport lead time.

Table 2

Impact of modularity on drivers within “Schedule” category

	Drivers	Positive effect of Modularity	Citations
Schedule	Activity sequencing	✓	Pan et al., 2023; Lerche et al., 2020
	Site disruptions and delays	✓	Pan et al., 2023
	Weather dependency	✓	
	Design and engineering lead time		
	Transportation lead times	✓	Abdul Nabi & El-Adaway, 2022; HUD, 2023
	Commissioning and testing	✓	Abdul Nabi & El-Adaway, 2022

Impact of Modularity on Safety & Quality

In this section, the authors present an overview of articles examining the utilization of modularity to enhance drivers of offsite construction within the "safety and quality" category (Table 3). Despite adhering to safety best practices, occupational safety remains a concern in the US construction industry. Studies indicate that offsite construction reduces accidents by moving complex work offsite, decreasing the number of on field workers, and reducing work conducted at elevated heights (Jeong et al., 2022). The familiarity of workers with modules, as discussed earlier, contributes to the advantage of the learning curve.

Table 3

Impact of modularity on drivers within the “Safety and Quality category”

	Drivers	Positive effect of Modularity	Citations
Safety and Quality	On-site safety performance	✓	Jeong et al., 2022
	Workplace congestion	✓	Jeong et al., 2022
	Exposure to hazards	✓	Jeong et al., 2022
	Safety planning and communication		
	Quality control implementation	✓	Gharbia et al., 2023
	Inspection at manufacturing plant	✓	Gharbia et al., 2023
	Rework	✓	Gharbia et al., 2023
	Capacity and experience of manufacturer/supplier		
	Aesthetic	✓	Enshassi et al., 2020

Quality considerations in offsite construction encompass quality control, inspection, rework, and aesthetics. Subassembly manufacturing in offsite construction falls within the manufacturing domain, allowing the adoption of quality assurance systems and certificates led by the manufacturing industry. Certifications ensure that manufacturing facilities maintain quality control, inspection systems, and skilled personnel (Gharbia et al., 2023). Aesthetic issues may arise from the misalignment of structural and façade modules (Enshassi et al., 2020), and damage to components during the onsite assembly process is also a significant concern. Leveraging the learning curve of labor due to the use of similar modules can be advantageous when adopting offsite construction (O’Connor et al., 2016).

Prefabricated construction contributes to improved performance measures by reducing the time spent on onsite operations and commissioning (Abdul Nabi & El-Adaway, 2022).

Impact of Modularity on Environmental Drivers

In this section, the authors have discussed the use of modularity to enhance drivers of offsite construction within the "environmental" category (Table 4). When offsite construction is embraced, buildings are disassembled rather than demolished. Standardized assemblies can enable the reuse of modules in subsequent projects with lower budgets after disassembly. Arisya & Suryantini (2021) introduced the term Design for Disassembly (DfD) to describe an architectural design process that considers the disassembly of structures. Alongside this concept, researchers proposed a strategy for the interchangeability of modules between two different modular houses, aiming to reduce waste generated at the end of a building's lifecycle.

Table 4

Impact of modularity on drivers within the "Environmental" category

	Drivers	Positive effect of Modularity	Citations
Environmental	Environmental impact	✓	Arisya & Suryantini, 2021
	Material and construction waste management	✓	Arisya & Suryantini, 2021
	Energy efficiency		
	Green practices	✓	Arisya & Suryantini, 2021
	Site disruption	✓	Arisya & Suryantini, 2021
	Climate, weather, and resilience		
	Building comfort and IEQ		

Impact of Modularity on Design, Engineering, and Implementation of New Technology

In this section, an overview of articles examining modularity's impact on offsite construction in the "design and engineering" and "new technologies" categories have been provided (Table 5). The shift to offsite construction emphasizes the role of manufacturing in the project, requiring adjustments in architectural design processes. The crucial concept of Design for Manufacturing and Assembly (DfMA) focuses on a smooth transition from design to manufacturing, with design modularity being a key principle (Jung & Yu, 2022). The integration of big data and Industry 4.0 technologies, including the Internet of Things (IoT), has significantly improved manufacturing processes (Yang & Lu, 2023). Turner et al. (2021) introduced a digital framework for distributed manufacturing in modular construction, emphasizing smart IoT integration for efficient adoption of the just-in-time concept, underscoring the importance of efficient manufacturing with modularity.

Transitioning from a project-based to a product-based approach involves viewing standardized modules as manufactured products. Eldamnhoury & Hanna (2020) explored this shift through interviews, aiming for vertical integration across design, manufacturing, and construction processes. Strategies included enhancing collaboration, integrating technology, and establishing a central project data hub. Standardized modules provide opportunities for design improvement. Peng & Kim's (2022) analysis of an Alabama-based offsite manufacturer's healthcare projects over 11 years highlighted efficiency gains with the Design-Manufacture-Construct (DMC) method, especially with the increased adoption of this approach.

Table 5

Impact of modularity on drivers within “Design & Engineering” and “Technology” categories

	Driver	Positive effect of Modularity	Citations
Design & Engineering	Standardization	✓	*McKinsey*, 2017; Peng & Kim, 2022
	Design flexibility and changes		
	Design freeze implementation	✓	Jung & Yu, 2022
	Technical and design feasibility	✓	Cinn & Song, 2015
	Use of repetitive design	✓	O’Connor et al., 2016; Cinn & Song, 2015
	Tolerance and interfacing considerations	✓	
Technology	Productivity	✓	Hadi et al., 2023; Peng & Kim, 2022
	Use of modern technologies	✓	Yang & Lu, 2023; Turner et al., 2021
	Efficiency and capacity of handling and lifting equipment		
	Efficiency and capacity of transportation modes and infrastructure*		
	Site attributes and logistics		
	Previous experience	✓	O’Connor et al., 2015

* Mentioned by the interviewee as a possible impact of modularity

Findings from Expert Interviews

Four subject matter experts (SMEs) were interviewed to further explore the role of modularity in the adoption of offsite construction within the US construction industry. Their insights centered on the significance of modularity and the primary impediments preventing the widespread adoption of offsite construction.

One SME, an architect with extensive experience in high-end residential and commercial offsite construction, emphasized the pivotal role of modularity in manufacturing. They stressed the need for developing product platforms tailored to market demands. The SME identified multifamily housing and complex structures like hospitals as the most conducive sectors for offsite construction adoption. Addressing internal barriers, such as a lack of modularization and technology integration, was contingent on first overcoming external barriers like regulatory hurdles, financial constraints, and challenges in project delivery and contracts. By addressing these external barriers, a favorable environment for offsite construction adoption could be established, allowing manufacturers to then tackle intrinsic barriers. Another SME, the founder of a prominent residential offsite construction manufacturing company in the US, identified multifamily and hospitality industries as having the greatest potential for offsite construction adoption. The efficiency achievable through repeatable modules was emphasized, with challenges in the single-family residential sector attributed to non-standardized dimensions and the demand for customized layouts hindering automated manufacturing technologies.

A different SME, the head of manufacturing for an offsite fabricator, asserted that incorporating modularity is imperative to make offsite construction affordable. Meanwhile, the founder of a firm dedicated to developing sustainable and affordable multifamily communities through offsite construction mentioned that without standard modules, achieving affordable housing would not be viable. Despite the importance of modularity, challenges surfaced during interviews, indicating reluctance from owners or developers to involve offsite manufacturers during the early stages of projects.

All SMEs emphasized that modularity is crucial for efficiency and profitability in offsite construction, potentially driving increased adoption. They also strongly advocated for nationwide building standards specific to offsite construction. Additionally, refining transportation laws to align with manufacturing needs, rather than limiting module dimensions, was highlighted as essential, especially for volumetric modules.

Conclusion

The objective of this study was to explore *how dimensional standards or modularity can influence offsite construction adoption?* Despite its historical use in the US since 1908, offsite construction has faced challenges in gaining a significant market share. However, a renewed interest has emerged, driven by increased housing demand and labor shortages. HUD (2023) conducted a comprehensive study, identifying gaps and outlining research directions across six domains. This study leveraged prior research, categorizing drivers found in existing literature into eight categories, further exploring how modularization enhances these factors. The authors adopted a two-part approach, commencing with a systematic literature review, followed by interviews with subject matter experts.

The literature review revealed that modularity can be used to enhance drivers of offsite construction within various categories. In the "cost and profitability" category, modularization could offer significant labor savings, potentially reducing construction time by almost half. Despite proven benefits, challenges exist, including initial capital costs and scalability concerns, necessitating further exploration. For the drivers under the “schedule” category, standardized modules may enhance predictability and reduce lead time, but challenges in U.S. transportation permits remain. In "safety and quality," offsite construction could further reduce accidents and offer quality control advantages, while aesthetic issues and damage during assembly are concerns. In the "environmental" category, disassembly and reuse of standardized modules could contribute to sustainability. Finally, in the "design and engineering" and "new technologies" categories, modularity is crucial for efficient manufacturing, with the integration of big data and IoT improving processes. Transitioning to a product-based approach and adopting delivery strategies like DMC show efficiency gains in offsite construction. During the interviews with the subject matter experts, both experts emphasized the need for modularity in driving increased offsite construction adoption.

Future research should focus on identifying the external barriers impeding the adoption of modularization in offsite construction. This study's findings highlight the potential of modularization in supporting the drivers for increased offsite construction adoption. The objective is to identify the root causes of these challenges, facilitating the development of intervention strategies. This approach is vital for fully realizing the potential of modularity and steering the future trajectory of offsite construction.

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