Modular and offsite Construction Summit
July 28–31,2025 Montreal, Canada

Barriers and Potential Solutions to the Adoption of Modular and Offsite Construction: A Review

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ABSTRACT
Modular and offsite construction (MOC) offer improved efficiency, sustainability, and flexibility in the construction industry compared to traditional methods. However, its widespread adoption remains hindered by various barriers. This paper presents a collaborative study conducted by researchers from Concordia University, the University of Alberta, and the National Research Council Canada (NRC) to identify and address these challenges. A comprehensive review of existing global research was conducted to identify barriers to MOC. These barriers were analyzed and categorized into six key groups: 1) Regulatory, 2) Economic, 3) Technical, 4) Organizational, 5) Workforce, and 6) Environmental. Additionally, recommendations to overcome these barriers are proposed and discussed. The findings from this study will serve as a foundation for a field survey to evaluate the significance of these barriers and assess their real-world impact within the current construction ecosystem. This study contributes to advancing MOC by identifying its barriers and supporting the industry's urgent need to adopt more sustainable and innovative alternatives to traditional construction methods.

KEYWORDS
Offsite construction; Modular construction barriers; Construction industry; Innovation; Review

INTRODUCTION
The construction industry is critical for economic growth but faces inefficiencies such as high costs, extended timelines, and environmental concerns (Razkenari et al., 2020). MOC offers a solution by improving efficiency, optimizing costs, enhancing sustainability, and ensuring quality control (Mao et al., 2016; Hong et al., 2016; Jin et al., 2020). For example, one study in Hong Kong showed that MOC could reduce construction waste by 56% and construction time by 20% (Jaillon & Poon, 2009). Despite these benefits, its adoption remains limited due to regulatory constraints, cost and affordability issues, limited design flexibility, and shortages in skills and experience (Rahman, 2014; Hatata et al., 2022; Sutrisna et al., 2022). This study identifies the key barriers to MOC adoption, categorizes them, and proposes effective solutions. The findings aim to

help overcome these challenges and encourage wider implementation. This paper is organized by a literature review, barriers categorization, solutions, and concluding remarks.

LITERATURE REVIEW

MOC involves relocating construction activities to an offsite environment and using prefabricated modules in the project delivery process, which helps improve project performance in terms of time and process efficiency (Lin et al., 2022; Wuni et al., 2023). However, its adoption is hindered by barriers such as technical complexities, limited industry knowledge, resistance to change, fragmented supply chains, high initial costs, and inadequate regulatory support (Ali et al., 2023). Without a clear understanding of these challenges, efforts to promote MOC adoption may remain ineffective, leading to industry resistance and continued reliance on traditional construction methods.

CATEGORIZATION OF BARRIERS

Regulatory Barriers

Outdated codes and unclear standards hinder MOC adoption, making compliance and quality assurance difficult (O'Connor et al., 2014; Sarbini et al., 2025). In Malaysia, regulations designed for conventional construction fail to accommodate modular systems, posing significant adoption challenges (Sarbini et al., 2025). In Sub-Saharan Africa, the lack of Building Information Modeling (BIM)-specific regulations and national standards for BIM creates challenges in standardization and approvals, making MOC integration more complex (Saliu et al., 2024). Meanwhile, the absence of a dedicated regulatory body leads to voluntary compliance, which, combined with unsound standards and a lack of effective incentives and policies, contributes to delays in project approvals and hinders the wider adoption of (Cheng et al., 2017)

Economic Barriers

MOC faces significant adoption challenges due to high upfront costs, particularly related to initial investment and transportation (Cheng et al., 2017; Patel & RazaviAlavi, 2022). The expense of prefabrication facilities and specialized equipment further limits financial feasibility (Li, 2023). In China, these barriers have slowed adoption compared to developed countries (Zhang et al., 2014). Low market demand in China also contributes to higher deployment costs, discourages developers, and reinforces reliance on conventional methods (Mao et al., 2015). In Perth's 18-storey modular hotel project in Australia, developers manufactured modules overseas to avoid the high cost of local production, underscoring financial constraints that limit broader adoption (Sun et al., 2020). Beyond direct costs, time-related inefficiencies such as delays in design finalization, production, and assembly can offset savings and create hesitancy (Mehdipoor et al., 2023).

Technical Barriers

Among the key technical barriers to MOC adoption are complex system interfacing, and the inability to finalize designs early (Pan et al., 2007). These issues are further compounded by design inflexibility, long lead-in times, and dimensional or geometric inconsistencies often caused by manufacturing flaws, material warping, or transport damage which lead to costly on-site adjustments (Shahtaheri et al., 2017). The process is further complicated by delayed contractor involvement, frequent design changes, and limited use of Design for Manufacture and Assembly (DfMA) principles and design automation, due to the need to regenerate drawings, poor coordination, and the lack of autonomous design-to-manufacturing systems (Said et al., 2017; Jensen et al., 2012; Sadoughi et al., 2020; Lu, 2017; Sadoughi et al., 2024). In addition, digital tools such as Radio Frequency Identification (RFID) and 3D simulation remain underutilized, often resulting in coordination gaps across project stages (Zhong et al., 2017; Sadiq et al., 2018).

Organizational Barriers

Knowledge shortages, limited manufacturing capacity, and logistical constraints hinder MOC adoption (Li, 2023). Additionally, restricted site access, inadequate storage, and complex module placement disrupt construction processes. These inefficiencies, combined with fragmented supply chains and poor scheduling, drive up costs and cause delays (Choi et al., 2019). Transport challenges such as oversized modules, permit restrictions, and congestion further reduce productivity (Li, 2023; Choi et al., 2019). A shortage of skilled contractors, resistance to innovation, and the absence of certification bodies also poses significant barriers. Moreover, limited supplier access, weak collaboration, and inadequate workforce training exacerbate organizational inefficiencies. Poor coordination, lack of stakeholder involvement, and ineffective leadership further hinder decision-making and project efficiency, underscoring the need for integrated delivery models and improved process management in MOC projects (Wuni & Shen, 2020; Ribeiro et al., 2022; Saad et al., 2023)

Workforce Barriers

The shortage of skilled labor in MOC, particularly in specialized modular trades, and manufacturing, is a major barrier to industry growth and limits production efficiency despite rising demand (Khan et al., 2024; Almughrabi et al., 2021). Most training programs still focus on traditional construction methods, resulting in poor adoption of prefabrication techniques (Chen & Samarasinghe, 2020). Additionally, the transition to offsite methods requires new technical and interpersonal skills that are not yet systematically addressed by education providers (Ginigaddara et al., 2019). Fragmented collaboration among designers, manufacturers, and builders restricts knowledge transfer, while the absence of standardized training and certification systems exacerbates skill gaps and complicates workforce allocation (Assaad et al., 2022). Beyond skill shortages, logistical inefficiencies, supply chain disruptions, and worksite congestion further reduce labor productivity, leading to delays and costly rework (Assaad et al., 2023).

Environmental Barriers

Despite MOC relative advantages in reducing waste and carbon emissions, it still faces environmental challenges (Alhawamdeh & Lee, 2024). High carbon emissions from production of materials like steel or cement is a challenge across the construction industry, including MOC (Karlsson et al., 2020). Additionally, the slow adoption of low-carbon materials and weak regulatory policies further hinder sustainability efforts (Karlsson et al., 2020). While MOC reduces onsite waste, inefficiencies in material cutting and excessive resource consumption generate substantial offsite waste (Thirunavukkarasu et al., 2021). The heavy reliance on cold-formed steel, high transport emissions, and limited use of renewable energy further exacerbate its environmental footprint. Moreover, the absence of deconstruction and recycling strategies prevents MOC from fully supporting a circular economy (Choi et al., 2019).

ADDRESSING KEY BARRIERS TO THE ADOPTION OF MOC

Regulatory Solutions

Razkenari et al. (2020) identified regulatory requirements as the most significant barrier to MOC adoption. China's integration of regulations with technology has accelerated adoption, serving as a global model (Chang et al., 2018). Government support programs and regulator training can further enhance compliance and drive adoption. In the study conducted by Marwan et al. (2022), which was based on cross-country survey data, the authors analyzed questionnaires and offered comparative insights into approaches such as self-certification and third-party certification. According to this study, Sweden relies on self-certification, Switzerland combines it with third-party oversight, and the UK enforces independent certification. China follows self-certification with government backing, while Australia's National Construction Code (NCC) remains voluntary, placing compliance responsibility on manufacturers. These models highlight how self-regulation, third-party oversight, and policy reforms can facilitate MOC adoption.

Economic Solutions

Lowering MOC's high upfront costs requires government funding, tax breaks, and improved expenses, while mass production and uniform regulations further stabilize costs (Chiang et al., 2006). Affordable financing options, including lower interest rates and modular loans, attract investment (Sadoughi et al., 2024). Optimized logistics planning, such as Just-in-Time (JIT) delivery and improved module packaging, enhance efficiency (Sun et al., 2020). Technologies like BIM and automated lifting systems further cut labor and equipment costs, improving modular construction's economic feasibility (Sun et al., 2020). Early collaboration and long-term supplier-builder relationships also enhance design coordination and project success (Ajayi et al., 2016).

Technical Solutions

To address technical challenges in MOC, countries like China, the UK, the US, Australia, and Singapore are adopting DfMA to improve standardization, precision, and automation through government policies and industry collaboration (Widanage & Kim, 2024). DfMA, lean construction, and automated fabrication streamline MOC by reducing waste, enhancing precision, and optimizing assembly (Langston & Zhang, 2021). BIM, Internet of Things (IoT)-enabled tracking, RFID workflows, and cloud-based data sharing improve supply chain coordination and quality control, minimizing errors (Zhong et al., 2017). BIM-based automation tools like MCMPro enhance collaboration, scalability, and cost-effectiveness (Alwisy et al., 2019). Advanced connection methods, such as high-strength bolted mechanical systems for steel modules further reduce onsite labor, cut material waste, and boost assembly efficiency (Zhang et al., 2020).

Organizational Solutions

Overcoming organizational MOC requires a multi-level approach. At the macro level, targeted education can address cultural resistance and promote MOC's benefits in cost, efficiency, and sustainability (Wuni & Shen, 2020). Organizational strategies like Integrated Project Delivery (IPD) encourage early collaboration and shared responsibilities (Hall et al., 2014), while vertical integration aligns manufacturing with supply chain operations for better coordination (Steinhardt & Manley, 2016). Digital tools, particularly when combining BIM with IPD, enhance real-time communication, reduce delays, and improve cost predictability (Li, 2023). At the workforce level, recruiting and upskilling in design, manufacturing, and installation is essential to support the shift between offsite and onsite environments (Almughrabi et al., 2021).

Workforce Development Solutions
Developing a skilled MOC workforce requires education, training, and standardization. Universities and apprenticeship programs should integrate MOC-specific curricula, while certification systems uphold industry standards. BIM-enhanced training improves design coordination and execution (Assaad et al., 2022). Standardized processes like Lean Manufacturing, Standard Operating Procedures (SOPs), and Production Breakdown Structures (PBS) enhance workflow efficiency and reduce waste (Zhang et al., 2020). With labor accounting for nearly half of construction costs, RFID technology optimizes workforce logistics by providing real-time data on worker movement, improving staffing, reducing delays, and maximizing productivity (Costin, Teizer, & Schoner, 2015). Additionally, public-private collaboration is crucial for funding upskilling initiatives and addressing labor shortages. Enhancing trade alignment, workspace optimization, and supply chain efficiency will further boost workforce productivity (Assaad et al., 2023; Rahman, 2014).

Environmental Solutions
Eco-friendly approaches like the use of rooftop solar panels (Faludi et al., 2012), cross-laminated timber (Lehmann, 2013), and energy-efficient flooring (Lee et al., 2014) reduce MOC's environmental footprint. Futhermore, energy-efficient design, circular economy principles, and Life Cycle Assessment (LCA) enhance material use (Ali et al., 2023; Zhong et al., 2017). Lean construction optimizes resources and minimizes waste (Nahmens & Ikuma, 2012), and efficient transport scheduling with standardized packaging lowers urban environmental impacts (Choi et al., 2019). IoT and BIM improve resource management, streamline planning, and cut transport emissions (Zhong et al., 2023), while BIM-RFID integration boosts monitoring and reduces waste (Darko et al., 2020). Together, these advancements make MOC more sustainable by cutting carbon emissions and enhancing efficiency.
This study did not fully capture emerging trends and regional differences in MOC adoption. In addition to the MOC barriers categorized in this study, other existing barriers such as social, cultural, or political factors need to be investigated in future work. It also did not incorporate input from diverse stakeholders, which could help improve the identification of barriers and the development of solutions related to MOC adoption.

Conclusion
MOC offers significant benefits, including efficiency, cost savings, sustainability, and reduced labor dependency. Despite its potential, adoption remains limited due to various challenges. This study identifies and categorizes these barriers into six key areas: regulatory, economic, technical, organizational, workforce, and environmental. It also proposes targeted solutions to support broader implementation. Future efforts should focus on stakeholder-specific strategies, improved collaboration between industry and academia, standardized life cycle assessments, and the integration of renewable energy solutions, and the development of a stakeholder survey to validate and prioritize the identified barriers to ensure the long-term viability of MOC.

Acknowledgements
The authors acknowledge the financial support of the National Research Council of Canada (NRC) Construction Sector Digitalization and Productivity Challenge program (CSDP) under Agreement #CSDP011-1, titled "Transformation from Conventional to Industrialized Construction".

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