Offsite Construction for Housing: Research Roadmap

U.S. Department of Housing and Urban Development | Office of Policy Development and Research

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PREPARED FOR:

U.S. Department of Housing and Urban Development
Office of Policy Development and Research

PREPARED BY:

Professor Ryan E. Smith
Founding Partner, MOD X
Director, School of Design and Construction, Washington State University

Professor Ivan Rupnik, PhD
Founding Partner, MOD X
Northeastern University, Associate Professor

Tyler Schmetterer
Managing Partner, MOD X

Kyle Barry, PMP
Senior Project Manager, National Institute of Building Sciences

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- Ryan E. Smith, Washington State University, MOD X, PTC Co-Chair
- Ivan Rupnik, Northeastern University, MOD X, PTC Co-Chair
- Tyler Schmetterer, MOD X, PTC Co-Chair
- Tedd Benson, Bensonwood / Unity Homes
- Cindy Davis, State of Virginia, and ICC President
- Carol Galante, University of California Berkeley, Terner Center for Housing
- Helena Lidelow, Lindbäcks Bygg AB and Lulea University
- Sara Ann Logan, Volumetric Building Companies
- Lisa Podesto, Lendlease
- Cheryn Metzger, Pacific Northwest National Laboratory
- Justin Stewart, Synergy Modular / Synergy Inc.
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The authors finally thank members of the NIBS Offsite Construction Council, who helped to seed the proposed research topics and questions, and volunteer members from across the offsite construction housing industry who participated in a workshop to review the proposed research topics and questions. The NIBS Offsite Construction Council and workshop participants are listed in appendix A.

II. Foreword

Addressing housing supply constraints in the United States requires an "all-of-the-above" approach that includes tailoring solutions to communities' specific housing challenges and marshaling resources at scale to address these challenges. Whether building housing for renters or homeowners, HUD is working to ensure that housing demand will be matched by the production of new homes that are affordable and accessible in every community.

HUD is also committed to leveraging technology and innovation to expand the supply of affordable housing that responds to diverse community needs across the United States. In the late 1960s and early 1970s, HUD embarked on an ambitious national program called Operation Breakthrough to stimulate production of quality housing for all income levels. Factory-built housing offered a promising means — then as it does now — for the housing industry to grow and progress. Operation Breakthrough impacts have been mixed. It helped shape the HUD code for manufactured housing, but adoption of the technologies and techniques it tested has been slow, with just a few components, such as factory-built wood trusses and walls, gaining market share in recent decades. There have been many technical innovations in our nation's housing delivery supply chain, yet factory-built housing and offsite construction, continue to struggle with scale and uptake. This stands in stark contrast to mature international offsite construction industries, such as those in Japan and Sweden. However, the Biden-Harris Administration's Housing Supply Action Plan includes significant new actions that would make it easier to build and finance offsite construction.

HUD is pleased to present the Offsite Construction for Housing: Research Roadmap, which introduces key concepts in offsite construction for housing and identifies key knowledge gaps that, if filled, could unleash the potential of offsite construction to help meet the country's growing housing needs. The report presents a research roadmap developed by national and international stakeholders and cross-sector experts. It suggests research topics to be addressed to overcome obstacles that prevent growth and market penetration for the offsite construction sector, while simultaneously providing recommendations for HUD to consider. The report is intended to be an industry wide roadmap for identifying the topics and questions for which the housing and offsite construction sectors can focus their research and development efforts.

These research topics included in the report complement HUD's Learning Agenda, and we hope industry stakeholders and other government agencies at the federal, state, and municipal level can use this roadmap as a guide to strategically focus on the offsite construction needs and programs to facilitate housing innovation and affordability.

Solomon Greene
Principal Deputy Assistant Secretary for Policy Development and Research
U.S. Department of Housing and Urban Development

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1 Executive Summary

The United States is in a housing crisis. Increasing prices for buyers and renters are forcing Americans out of their homes and making housing unattainable. *Offsite construction*, the design and delivery of housing using an industrialized and manufactured-style approach, has the potential to deliver more affordable and accessible single and multifamily housing at scale. Although there are many documented benefits to offsite construction, including schedule improvements, quality control, worker safety, and reduction of environmental impact, as an evolving method and practice, offsite construction for housing faces several challenges to increase uptake and adoption. This report, the Offsite Construction for Housing Research Roadmap, presents the key knowledge gaps and research needs that are to be addressed to overcome the barriers and challenges of offsite construction. It is intended as a roadmap for HUD to align its programs and partnerships, but can also serve as an industry-wide roadmap that governments, universities, and offsite companies can work on together to progress offsite construction for housing.

Given HUD's desire to develop a roadmap based on the needs of the industry, NIBS and MOD X enacted the following development structure of three phases: Phase 1) develop a preliminary list of core research topics and questions with the NIBS Offsite Construction Council; Phase 2) conduct a literature review and form a PTC of leading experts representing the housing and offsite construction industry to refine the topics; and Phase 3) hold an invitation-only workshop to review, validate, and prioritize the research questions. The resulting report was sent to the PTC for peer review and comment, and a final draft was issued. Using this industry consensus process, the following six topical areas emerged, listed in order of priority:

- Research Topic 1: Regulatory Framework.
- Research Topic 2: Standards and System Performance.
- Research Topic 3: Capital, Finance, and Insurance.
- Research Topic 4: Project Delivery and Contracts.
- Research Topic 5: Labor and Workforce Training and Management.
- Research Topic 6: Business Models and Economic Performance.

Under each topic, subtopics were identified with specific research questions listed to answer the knowledge gaps. Although the six topics and associated subtopics in this report are not definitive, they do represent what industry experts—stakeholders that engage with offsite construction for housing in their daily practices—consider to be the most pressing concerns, obstacles, and opportunities for which research can provide answers. Although the research topics in this roadmap include technical obstacles and barriers, many challenges identified by the participants stem from the social, environmental, and economic context that negatively impacts offsite construction for housing today.

Some of the offsite construction for housing topics can be researched and addressed discretely; however, many of the topics are contingently related to one another. This Research Roadmap suggests that the resolution of knowledge gaps in regulations, standards, capital, finance, and insurance is a higher priority than project delivery, contracts, labor, workforce, and business models. It is also important to note that each topic will require research and action within the

offsite construction industry as well as the broader context in which offsite construction operates. In addition to the topic identification, prioritization, and contingent relationship between topics in this roadmap, there are also several key takeaways from this consensus process in developing the report:

Key Takeaway 1: Research is Knowledge Production and Knowledge Sharing
For offsite construction to improve and accelerate in growth and impact on housing, more knowledge needs to be produced and made available to promote a research culture. This needs to be balanced with the commercial interests of offsite construction stakeholders for intellectual property.

Key Takeaway 2: Fewer Disciplinary Silos, More Interdisciplinary, Cross-Cutting Research
Most barriers and knowledge gaps identified through this report are situated at the intersection of means and methods internal to the industry and the context in which it operates: regulatory, finance, standards, workforce, contracts, and business models. This requires different disciplinary and organizational expertise working in a collaborative manner. It is also recommended that the federal agencies partner with each other and with municipal and state governments to co-fund research in offsite construction for housing.

Key Takeaway 3: Data are the Keys for Continuous Improvement
For offsite construction to compete with traditional construction, it must continuously become more industrialized, with improving data being central to demonstrating value and delivering on its potential.

Key Takeaway 4: Documentation and Dissemination of U.S. Best Practices and Lessons Learned
There are several municipal and state initiatives to foster and accommodate offsite construction growth, including zoning revisions, finance vehicles, patient capital programs, offsite construction project request for proposals (RFPs), etc. Related to data gathering, performance of these programs, initiatives, and the associated lessons need to be more fully studied, analyzed, documented, and disseminated.

Key Takeaway 5: Pilot Projects are Key to Demonstration and Adoption
This recommendation is for pilot projects to demonstrate not only technical means and methods, but first and more importantly, an understanding of the regulatory, standards, and finance topics is essential.

Key Takeaway 6: Education and Training are Key for a Secure Knowledgeable Workforce
Education and training are needed early, often, and throughout offsite construction business and project practices. Furthermore, there is a need to address and fund higher education, trade schools, and apprenticeship programs for cultivating job growth and recruiting labor into offsite construction.

Key Takeaway 7: Learn Globally, Act Locally
This report identifies the need for lessons from abroad in nearly every topical area. There is a need for comparative research projects about international offsite construction programs that bring together industry, academia, and government to improve housing for everyone.

The list of research needs for offsite construction in this report is intended for the offsite construction industry broadly. There are some projects, however, for which HUD is uniquely situated to address within its interests and capacity. The text below outlines research recommendations specifically for HUD to enact as projects, partnerships, and initiatives:

Knowledge Platform: Foster a knowledge production, management, and sharing platform for industry, government, and universities to communicate best practices and lessons learned, while also protecting intellectual property.

Data Culture: Create a data collection and data analysis process for offsite construction metrics to both claim the benefits the industry purports and improve the areas in which it is underperforming as an industry for continuous improvement.

Taking Stock: Support the comprehensive review of Operation Breakthrough, Partnership for Advancing Technology in Housing (PATH) and other HUD efforts, as well as state and local government initiatives in offsite construction, both historical to contemporary, and their individual and collective impact on housing innovation, affordability, and access.

Demonstration Projects: Facilitate and co-fund pilot projects for new technologies, policies, finance structures, project delivery/contract structures, and workforce programs for offsite construction to determine the impact and provide models.

Educating Authorities Having Jurisdiction (AHJs): Develop an offsite construction education and training program for code officials and other gatekeeping stakeholders.

HUD Code: Investigate the relative merits of the HUD Code versus the ICC codes for potential regulation of manufactured housing.

New Products: Research the obstacles of the current ICC-Evaluation Service (ES) process to develop mechanisms to foster new product development in offsite construction for the housing sector.

Design Standards: Develop a product platform for affordable and attainable multifamily housing with standards and specifications that can be shared between manufacturers as a rapid housing initiative to address the housing crisis and homelessness.

Supply Chain: Evaluate the impact of poor-quality sawn lumber supply chain for offsite manufacturing and develop alternatives. Investigate how offsite manufacturing can help alleviate supply chain issues in housing construction more broadly.

Capital: Work with local and state governments and NGO investors to co-fund a patient capital grant or loan program to foster supply-chain migration and start-up funding for offsite manufacturers.

Finance: Partner with Fannie Mae and Freddie Mac to develop a bridge-funding vehicle for offsite construction early-stage finance for factory deposits, and design documentation assistance associated with offsite construction.

Skills and Training: Support an offsite construction workforce and a trades-training and certification program to improve factory labor practices and onsite assembly quality control, as well as partnerships with union labor organizations.

Vertical Integration: Research the particulars of vertical integration for offsite construction to determine the benefits, challenges, opportunities, and obstacles, and share successful models domestically and internationally, for offsite construction.

Customer Centric: Study examples and share best practices of customer-centric enterprise for optimizing a product-based approach to offsite construction for personalization and productivity.

Federal Partnerships: Establish a program to co-fund offsite construction for housing research with other federal agencies to rapidly advance knowledge and offsite construction practices and performance.

Local Partnerships: Co-fund RFP projects with municipal and state programs to foster offsite construction capacity and capability. Collect and share case studies of local zoning efforts and policy initiatives to foster offsite construction for housing.

International Partnerships: Foster an international network of partners between HUD and offsite construction housing organizations in Japan, Sweden, Australia, the United Kingdom (Scotland), and other parts of Europe for knowledge sharing and co-funding research.

1.1 About the Authors

MOD X is an industrialized construction research and education network and consultancy. MOD X fosters a growing global network of individuals and organizations interested in advancing industrialized construction through knowledge exchanges via symposia, factory and site tours, and business support. MOD X provides research solutions, including market surveys and analysis, product R&D, business planning, and technology transfer for the international design, manufacturing, and construction industry. The group objectively evaluates the potentials and problems of offsite construction to consider a more ecological and economical approach. As leading researchers of volumetric modular construction, MOD X provides a current and comprehensive assessment of past, present, and future trends in the industry, and it offers a cultural and economic evaluation of innovation diffusion that is customized to the needs and interests of our clients and partners. Additional information about MOD X Network and MOD X Exchanges is available at www.modx.network. MOD X authors include:

Ryan E. Smith, Founding Partner of MOD X and Professor and Director of the School of Design and Construction at Washington State University.

Ivan Rupnik, Founding Partner of MOD X and Associate Professor of Architecture at Northeastern University.

Tyler Schmetterer, Managing Partner of MOD X and award-winning producer of offsite manufacturing projects focused on high-performance and sustainable residential housing.

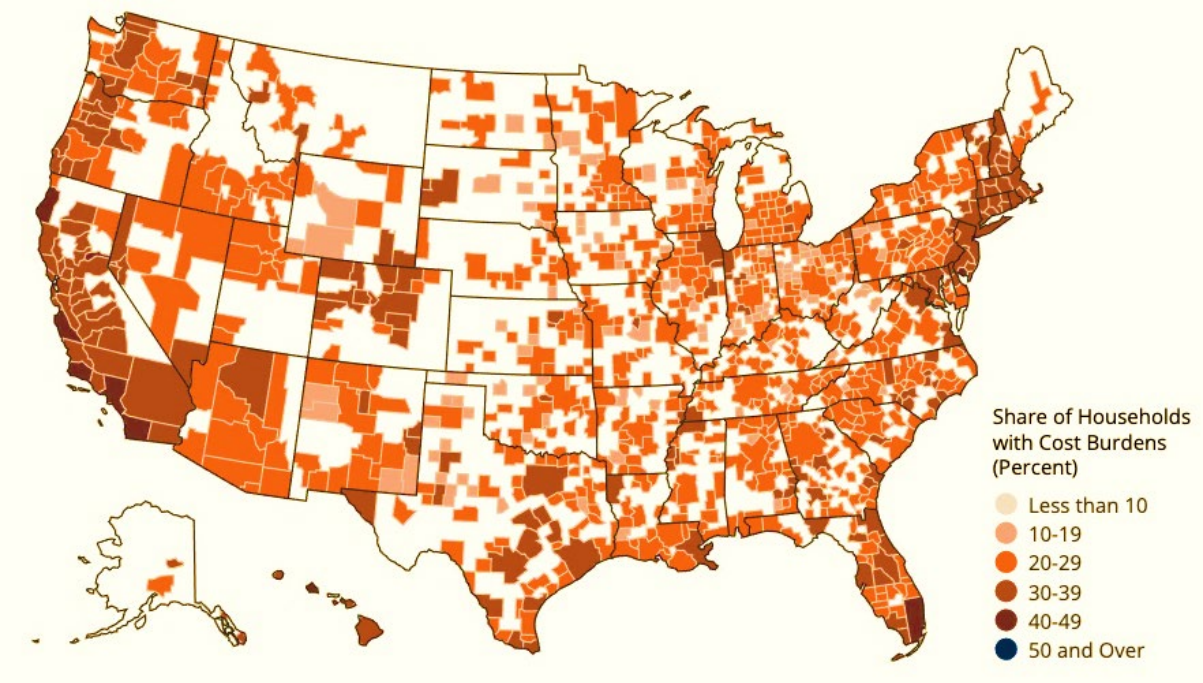
The **National Institute of Building Sciences (NIBS)** was established by the U.S. Congress in 1974 as an independent organization that brings together the building industry, labor and consumer interests, government representatives, and regulatory agencies to identify and resolve problems in the built environment. For more than 40 years, NIBS has gathered the industry to tackle challenges and find solutions. It assembles federal, state, and local government agencies and representatives of the private sector for open work sessions to solve problems of mutual concern. NIBS has conducted many national studies that lead the direction of the building industry and provide scientific information for policymaking. NIBS strives to provide independent and consensus information through its various councils and committees, including in offsite construction. Through its Offsite Construction Council (OSCC), NIBS serves as a research, education, and outreach center for relevant and current information on offsite design and construction for commercial, institutional, and multifamily facilities. More information about the council is available at www.nibs.org/oscc. The NIBS author is:

Kyle Barry, PMP is Senior Project Manager at NIBS and currently serves as the staff liaison to the NIBS Offsite Construction Council.

2 Introduction to Offsite Construction for Housing

In the United States today, nearly one in three American households is cost-burdened, spending more than 30 percent of their income on housing (JCHS, 2016). Increasing costs for buyers and renters, and the increasing expense of maintenance and operations, are forcing some Americans out of their homes and preventing many others from finding reasonably affordable housing (exhibit 1). Although this once was a problem reserved for larger cities such as San Francisco and New York, it is now also affecting developing cities, suburbs, and small towns that are rapidly growing and gentrifying (Henderson, 2019).

Exhibit 1. Cost Burdened Households that Spend More than 30 Percent of Their Income on Housing



Source: Harvard JCHS, 2019

McKinsey Global Institute (Woetzel et al., 2014) claims that there are several strategies that can optimize the cost of housing by as much as 50 percent, including: unlocking land supply through regulatory reform toward more inclusionary land-use policies and reducing the complexity and cost of entitlements, lowering finance costs for both buyers and developers, improving operations and maintenance of the housing stock, and reducing construction costs. Ivory Innovations (2020), a housing affordability think-and-do-tank, and The Housing Lab (2020), associated with the Terner Center for Housing Studies at University of California, Berkeley, corroborate that policy and regulatory reform, finance and advocacy revision, design, construction research, and innovation diffusion are pathways to achieving greater housing access and affordability. *Offsite construction*, a design and construction innovation, is one of the practices that have the potential to deliver more affordable and accessible single and multifamily housing at scale (Barbosa et al., 2017; Bertram et al., 2019; NRC, 2009)

Offsite construction can be defined as "the process of planning, designing, fabricating, transporting, and assembling building elements in a factory setting for rapid onsite assembly to a greater degree of finish than in traditional piecemeal onsite construction." (Smith and Quale, 2017). This definition, however, is evolving as an emerging practice of building delivery in the United States, and it is not necessarily an established industry. Furthermore, offsite construction is only one part of a dynamically growing set of practices and methods that are intended to improve productivity in housing construction (Barbosa et al., 2017). Other terms are often used interchangeably with offsite construction, but those terms are unique and should be considered in the context of productivity practices.

Industrialized Construction uses industrial, manufacturing-based principles and production methods such as advancements in computing, automation, construction planning and management, and materials science for greater productivity. These principles can be applied to onsite (e.g., Levittown [Carlisle, 2009][1] or 3D printing) and/or offsite construction conditions. *Offsite construction*, therefore, is one of many industrialized construction approaches; it leverages the factory environment to create value added *subassemblies*—to take a term from product manufacturing—of various degrees of prefabrication, ranging from 1D (Kit of Parts) to 2D (Panelized) to 3D (Volumetric) to complete structures (HUD Code "manufactured homes"). *Modularization* (Schuh et al., 2017; Martin, n.d.) is an approach to offsite construction that uses the principles of *Design for Manufacture and Assembly* (DfMA) (Gao, Jin, and Lu, 2020; Lu et al., 2021) and predefined *Product Platforms* to allow for project reconfigurability and adaptability through a set of standards, interchangeable and continually improvable subassembly elements (2D or 3D) (Harland, Uddin, and Laudien, 2020). The subassemblies may serve different *Building System* functions, including structure, enclosure, finishes, mechanical/electrical/plumbing services (MEP), etc. The ICC/MBI Standard Toolkits provide more context and definitions of offsite construction industry accepted terminology (ICC, 2020). Section 2.1 in this report clarifies key concepts and terms that are emerging in the growing offsite construction for housing practice referenced herein.

Like any method or practice that is evolving and maturing, offsite construction for housing is fraught with challenges and opportunities, trade-offs, and unrealized potentials. Offsite construction has demonstrated improvements to vertical construction project productivity and performance in cost, schedule, and fewer change orders (Pan, Gibb, and Dainty, 2012). Offsite construction offers improvements in worker safety (ILO, 2005; US BLS, 2009; Court et al., 2009), the potential for training and skills (Nutt-Powell, 1985), and reductions in ecological impacts of building construction (Quale, et al., 2012; Tam and Tam, 2006; Pons-Vallardares and Wadel, 2011). These studies, however, are case examples, demonstrative of what is possible with offsite construction, and they are not necessarily definitive or reliable best practices to be applied to future projects and the establishment of offsite construction for the housing industry. Conversely, offsite construction also has associative challenges, including regulatory barriers, financing gap concerns, material supply chain disruptions, design-to-manufacture software incompatibility and workflow obstacles, factory pipeline inconsistencies, cultural and social

[1] Levittown is a suburban housing development model employed in several locations in the United States, built for returning WWII veterans and their families in the 1950s. The development and construction model used a production assembly line approach to site construction organization of labor and materials. Levittown built a slab-on-grade house each day using an industrialized site construction method with 36 men (exhibit 4).

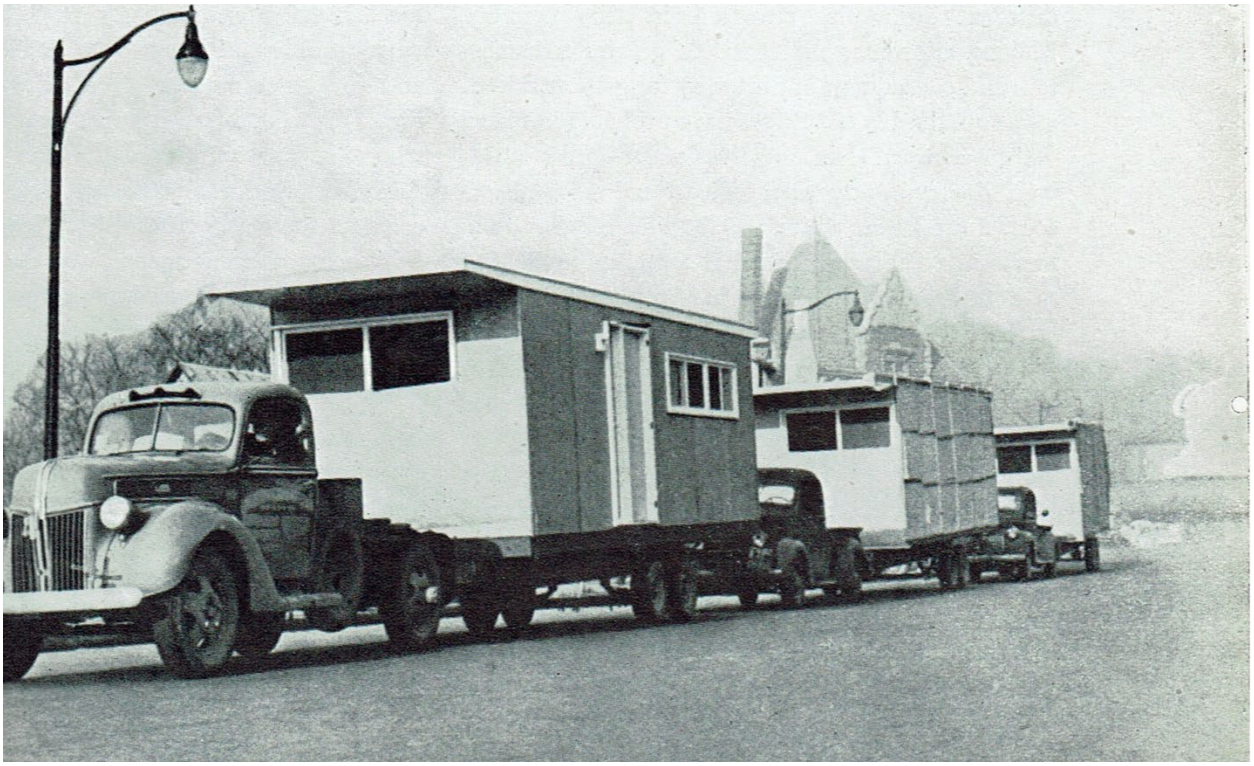
barriers, and transportation complications (Smith, 2015, 2018). Although labor is limited across the construction sector, in offsite construction, challenges with the workforce also persist, such as union roadblocks, layoffs due to inconsistent factory volume, recruitment, training, and the lack of capacity and capability of offsite manufacturers and suppliers (Smith 2015, 2018; Sisson, 2018). Prior research has identified the challenges to increased adoption and supply of offsite construction at a high level. This research report seeks to qualify the significance of these barriers with industry experts—stakeholders that work on housing and offsite construction every day. The intention of this report is to provide a roadmap to overcome these obstacles through research, accelerating the development and growth of the offsite construction housing industry in the United States.

Offsite construction is not new; it was first applied to housing in the United States around the turn of the last century and exported abroad during the interwar period (Rupnik, 2015; Oshima and Waern, 2008). During the immediate postwar period, growth of offsite construction in European and Asian countries increased through government-sponsored programs designed to meet the massive worldwide housing crisis (Rupnik, 2015; Kelly, 1951; Bruce, 1945). These programs ensured a steady demand for the fledgling offsite construction industries in those countries, lowering the risk for the significant capital investment required for any manufacturing industry. The general stagnation of population growth and the energy crisis (which directly impacted the transportation cost of highly prefabricated concrete systems) led to a significant decline of the use of offsite construction in much of Europe and Asia. Two important exceptions to this decline are Sweden in Europe and Japan in Asia, two countries whose initial public investments in expanding offsite construction were followed by a series of industry-led and sponsored standardization initiatives that have maintained and even increased the offsite construction market penetration up to the present day (Rupnik and Smith, 2018; Smith, 2009). A new massive worldwide housing crisis, combined with the climate and labor crisis, has in turn led to a renewal of interest for offsite construction globally (Woetzel et al., 2014).

Prefabricated housing started to see use in the United States during the interwar period as well; however, there was little uptake beyond purpose-built pilot projects such as the Tennessee Valley Authority public works project (exhibit 2), which did not have a wide market impact, but those projects did pave the way for mobile homes and a larger follow-on project after World War II (Kelly, 1951; Darnall, 1972; Raskin and Bennet, 1936; Smith, 2010). Influenced by the success of international programs and public-works prefabricated homes domestically, HUD initiated a similar initiative called Operation Breakthrough (Patman et al., 1968). Operation Breakthrough (exhibit 2 and 3) endeavored to "demonstrate the value of industrialized (factory-built) housing construction methods" and to "eliminate and reduce barriers to industrialized construction" by subsidizing several demonstration projects across the country (Staats, 1976). In 1976, the $72,000,000 program (nearly $500,000,000 in today's dollars) was deemed a "failure" by the United States Congress (McCutcheon, 1992). However, an assessment of the program did acknowledge the creation of a series of changes and additions to existing regulations that reduced barriers to the growth of the U.S. domestic offsite construction industry (Staats, 1976). One of the most direct results of Operation Breakthrough was the HUD Code, often referred to as "manufactured homes," which at its peak in 1998 constituted one out of every three (~33 percent) single-family homes and today constitutes 10 percent of the single-family housing market (MHI, 2021).

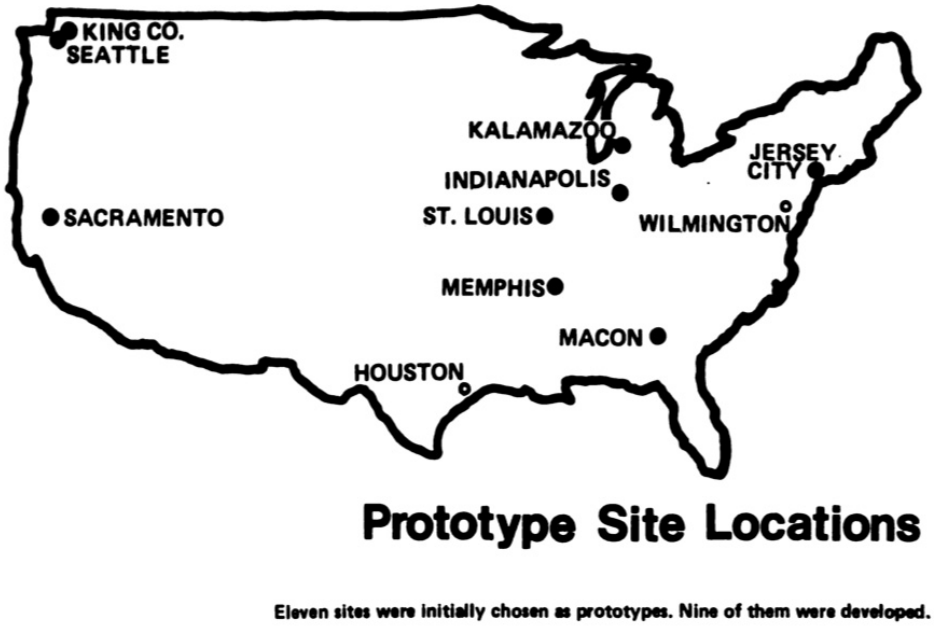
The HUD Code eliminated several barriers to offsite construction through product and process standardization, but it did not resolve certain regulatory and financing barriers, which can be attributed in part to the program's recent decline (MHI, 2021). The HUD Code home industry has also lacked the incentive for competition and innovation that the publicly initiated and industry-supported refined offsite construction programs of Sweden, Japan, and other mature offsite construction sectors have developed over the last 50 years. Nevertheless, Operation Breakthrough and the HUD Code program supported the development of routine inspection and transportation of prefabricated building components, enabling the growth of the volumetric modular construction industry, currently the largest in the world in terms of total value (3.4 percent of total construction value in the United States) (Rupnik, 2017, 2019). In other words, without this so-called "failure," offsite construction in the United States would arguably not exist in its current form, despite inadequate research and analysis of the program failures and positive market impacts.

Exhibit 2. Prefabricated Housing in Transit for Workers that Were Building 16 Hydroelectric Dams in the Tennessee Valley Sanctioned by President Franklin D. Roosevelt between 1933 and 1944



Source: U.S. Department of Housing and Urban Development (HUD)

Exhibit 3. HUD Operation Breakthrough (1969) Selected 11 Sites for Housing Prototype Locations, with 9 that Were Developed



Source: U.S. Department of Housing and Urban Development (HUD)

Since Operation Breakthrough, HUD created PATH—Partnership for Advancing Technology in Housing—as a public/private partnership to develop, demonstrate, and gain widespread market acceptance of new technologies for the next generation of U.S. housing. PATH ran during the late 1990s and early 2000s, and it involved a number of federal, state, and local jurisdictions, manufacturers, and builders to investigate housing technology questions. Researchers included the NAHB Research Center (now called Home Innovation Research Labs), Virginia Center for Housing Research at Virginia Tech University, and Steven Winter Associates, among others. The goal of PATH was to "improve the quality, durability, environmental efficiency, and affordability of tomorrow's homes" (HUD, 2021). As such, PATH was focused on single-family detached HUD Code homes and IRC Code panelized and modular construction under the category of what HUD called "factory built." PATH's work led to the development of six technology roadmaps, including: Energy Efficiency in Existing Homes, Whole House and Building Process Redesign, Manufactured Housing (HUD Code), Information Technology and Advanced Panelized Construction, and Factory Built Housing Roadmap, in addition to numerous reports on discrete technical topics (HUD, 2021).

More recently, the Department of Energy (DOE) has launched the Advanced Building Construction initiative out of the Office of Energy Efficiency and Renewable Energy, Building Technologies Office. This effort acknowledges that energy efficiency in buildings will not be improved rapidly until the entire supply chain, the stakeholders, and the delivery processes for building construction and maintenance are addressed holistically. Energy-efficient technology integration projects are currently being conducted by researchers at national DOE labs and universities in partnership with panel and modular manufacturers and general contractors (GCs).

Concurrent to this HUD roadmap is a forthcoming related report—the Advanced Building Construction (ABC) Initiative Innovations Roadmap: Industrializing Construction to Decarbonize Buildings. This roadmap focuses on R&D and commercialization, with industrialized and offsite construction being specifically highlighted as an area for additional research discovery for new and retrofit development. The ABC Innovations Roadmap identifies some of the topics from this HUD Offsite Construction for Housing Research Roadmap including challenges with factory-to-site coordination, workforce training, financing for factories and offsite construction-oriented projects, and supply chain barriers (DOE ABC, 2021).

The lessons of HUD's Operation Breakthrough and subsequent efforts with PATH and DOE ABC illustrate that although offsite construction is technical, the barriers to realizing its application at scale are contextual, being contingent on the social, economic, and environmental situation in which is it employed. There is an increase in the use of offsite construction today (MBI, 2021) fueled by the availability of affordable mass marketing through social media channels, online webinars, the rapid pace of digital publishing, and international knowledge-transfer at scale not achievable in the past. Furthermore, investor interest in offsite construction has been promulgated by international management consultant McKinsey & Company (Bertram et al., 2019; Barbosa et al., 2017), who have claimed in their reports that a dramatic increase in productivity is possible by virtue of industrialization and offsite construction. Some of these investments have been ill-informed, not contextually dependent, and too reliant on technology alone (i.e., significant investment in automation without an assessment of value). The growing affordable housing gap, lack of available labor workforce, supply-chain and trade difficulties, and changing climate all point to the need to reconsider how to build better, delivering housing via industrialized means and offsite construction (Hairstans and Duncheva, 2020).

This report codifies a qualitative evaluation of the key research needs to take advantage of the promises of offsite construction while leaving its failures behind. Although these topics include technical obstacles and projects, the PTC and workshop participants also identified topics that stem from social, environmental, and economic forces that impact housing today. The topics range from regulations to finance and from education to business planning, with a goal to have offsite construction develop as a resilient U.S. industry into the future. Although these topics are not definitive, they represent what industry experts—stakeholders that engage with offsite construction for housing in their daily practices—consider to be the most pressing concerns, obstacles, and opportunities for which research can help address.

2.1 Key Concepts in Offsite Construction for Housing

The U.S. offsite construction housing sector is not new, but it is also not as mature as some other international contexts. One of the key characteristics of a mature offsite construction sector is common terminology that is consistent within the sector. Common terminology must also be compatible with other sectors, including manufacturing, from where the most significant knowledge exchanges occur; the broader architecture, engineering, and construction (AEC) sector of which it is a part; and the regulatory context. This clarity of terminology has supported confidence in offsite construction in international contexts more broadly, from potential investors and lenders to end users. The International Code Council (ICC) has made an important step in standardizing terminology (ICC/MBI, 2021), but this is only the first step in a necessary process in which HUD could have a significant impact, especially as offsite construction relates to

housing specifically. Following national and international best practices, MOD X has developed an overview of key concepts in offsite construction.

2.1.1 Industrialized Construction/Conventional Construction

Industrialized construction uses industrial, manufacturing-based principles and production methods such as advancements in computing, automation, construction planning and management, and materials science (Al-Hussein, n.d.) for greater productivity. These principles can be applied to onsite and offsite construction conditions. The most successful examples of this principle are to industrialize the offsite construction and onsite aspects of construction into a continuous whole (exhibit 4). This term was once used widely in the United States and was included in several early reports on the subject, including the seminal "Industrialized Building: A Comparison of European Experience," the 1968 HUD study that ultimately informed Operation Breakthrough. This term is still widely used abroad, and in the United Kingdom it has become synonymous with a new term, Modern Methods of Construction (MMC) (Davies, 2018).

Exhibit 4. Levittown, NY (circa 1951)—Industrialized Site Construction Using a Slab-on-Grade

Source: Levittown Public Library

2.1.2 Offsite Construction / Onsite Construction

Offsite construction is construction where some portion of the process is completed offsite in an enclosed environment. Although it is often assumed that offsite construction is also *industrialized construction*, in the U.S. context, there are plenty of examples of offsite construction that use little or no industrial means, methods, or technology. There are also examples of highly industrialized construction approaches that are entirely completed onsite (3D printing, for example). The equivocation of industrialized and offsite construction has often led to assumptions about productivity gains simply by moving construction under a roof, which have rarely proven to be true in practice. On the other hand, many mature offsite construction companies abroad choose to complete aspects of construction onsite instead of in the factory precisely because they have industrialized the entire process and can therefore make informed decisions about which aspects are better completed in an offsite environment. In the U.S. context, the term *factory-built* is also often used interchangeably with the term offsite construction. *Offsite manufacturing* is but one of the steps in offsite construction: the manufacturing portion in the factory. However, offsite construction is the entire process of design, manufacture, and onsite assembly of elements that have been prefabricated in a factory offsite. Offsite construction can be applied to many different building types—hospitality, office, institutional, etc. The focus of this report, however, is on housing typologies. Therefore, when referring to offsite construction herein, the default understanding is offsite construction for housing specifically.

2.1.3 Degrees of Enhancement: Open Structural Components, Enclosed Sections

An important but often overlooked terminological distinction, with significant impact on offsite construction, refers to whether a factory-built component is an enclosed section or an open one before it leaves the factory. *Enclosed* subassemblies are often inspected in a factory before being assembled onsite, whereas open structural components can be inspected onsite (exhibit 5). Enclosed subassemblies are inspected in the factory because the manufacturing of the element hides inspection-related systems within, making site inspection of structural, thermal, electrical, or other systems not visible. The subassemblies that are enclosed can be 2D panels, 3D volumetric modules, and 3D service pods.

Exhibit 5. Closed Panel Turnkey Manufacturer-Builder Bensonwood/Unity Homes in New Hampshire, USA

Source: MOD X

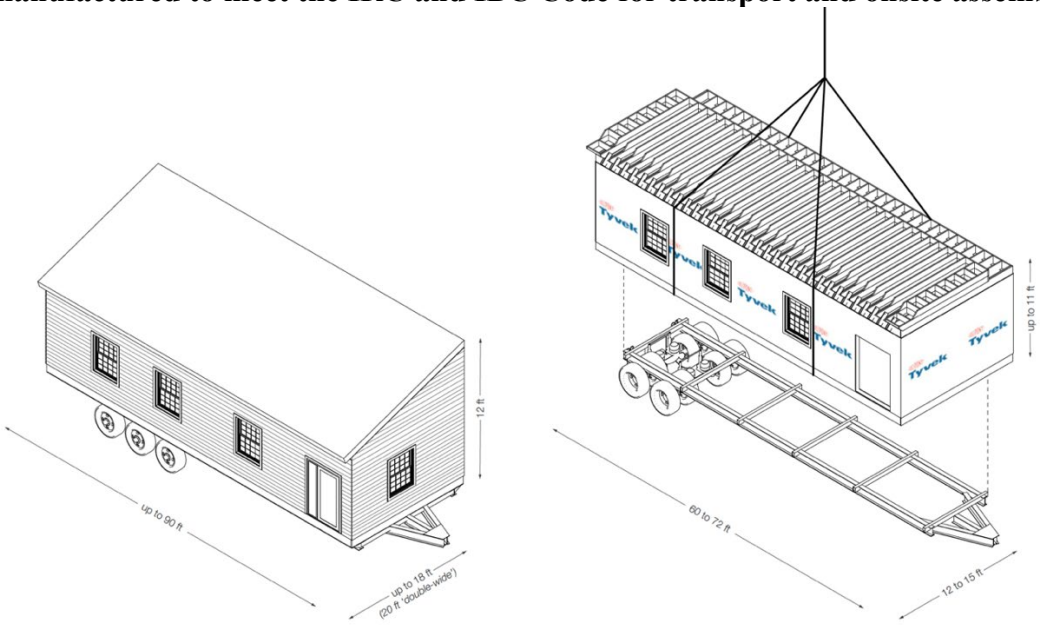
2.1.4 Degrees of Prefabrication: Kit of Parts (1D), Panelized (2D), Volumetric (3D), Factory-Built Structure (Complete Structure)

Offsite construction and associated offsite manufacturing are often organized into three categories of degrees of enhancement (or prefabrication) or level of completion/finish. *Kit-of-parts* (1D) systems are the most varied and include any system where a significant portion of the structure is fabricated in a factory as a set of components that will be assembled onsite into a particular structure. A variety of kit-of-parts systems exist in the U.S. market today, some of the most prevalent being log cabin kits. Panelized (2D) systems are made up of two-dimensional components, also sometimes referred to as *flatpack* systems.

Panelized systems vary widely, from open-panel structural components, in which only the primary structure is completed in the factory, to enclosed panel systems, in which structure, insulation, interior sheathing, exterior finishes, and other systems are fabricated offsite. Volumetric modular (3D), *permanent modular*, or simply *modular* systems, consist of enclosed three-dimensional building sections completed in the factory (Smith and Quale, 2017). Service pods are 3D or 2D kitchen and bathroom elements that integrate MEP to be installed in multifamily housing. Panelized, volumetric modular, and service pods are sometimes referred to as *subassemblies*, meaning elements that are brought to site to be finally assembled, borrowing

terms from the product manufacturing industry. Lastly, *HUD Code*[2], or *manufactured homes,* are single-wide or double-wide 100 percent factory-completed homes, and *relocatable buildings* are entirely complete factory-built structures used as construction site trailers and workman camp housing for resource extraction, among other temporary functions[3] (exhibit 6). Exhibit 7 outlines the more prevalent offsite manufactured components and subassemblies for housing.

Exhibit 6. In the U.S. offsite construction industry, the regulatory framework distinguishes between offsite construction systems that share several similar means and methods. HUD Code "manufactured homes" (left) are single or double-wide manufactured sections on a permanent trailer chassis. 3D Volumetric Modular or "permanent modular" are manufactured to meet the IRC and IBC Code for transport and onsite assembly.



Sources: MOD X/Northeastern University

[2] A HUD Code home is a single-wide or double-wide transportable section manufactured to the *HUD Manufactured Home Construction and Safety Standards, 24 CFR Part 3280,* administered by the U.S. Department of Housing and Urban Development (HUD Code). HUD Code homes were known as mobile homes until the 1970s and today are often referred to as "manufactured homes." HUD Code homes display a red certification label on the exterior of each transportable section. HUD Code homes are built in a factory like other offsite construction subassemblies; however, the key difference is that HUD Code homes are manufactured on a permanent trailer chassis. Also, unlike other offsite subassembly manufacturing that supply permanent IRC or IBC Code housing, HUD Code homes often are restricted by land use zoning policies and use a unique financing program for homeowners called the U.S. HUD Federal Housing Association Loan. The HUD Code prescriptive production requirements are intended to produce a minimum viable product as an affordable housing solution. For more information about HUD Code homes visit: https://www.hud.gov/program_offices/housing/rmra/mhs/faqs#:~:text=The%20HUD%20Code%2C%20unlike%20conventional,codes%20as%20site%2Dbuilt%20homes

[3] Relocatable buildings include factory-produced entire modules that are 100 percent complete in the factory and built on permanent chassis. As the name suggests, relocatable structures can be moved throughout their lifespans to serve occupants for a short-term or temporary durations of time. Examples of this type of offsite construction include portable classrooms, temporary office structures, emergency and disaster relief housing, workman camps common in resource extraction remote sites, and construction site trailers. For more information about relocatable buildings, visit: www.modular.org

Exhibit 7. Offsite construction systems categories with their associated descriptions. This table explains the physical characteristics of each system, examples of system categories, and the applicable codes in which they are permitted and inspected by the *Authority Having Jurisdiction* (AHJ).

Offsite Construction System	Description
1D Subassembly	• Kit-of-parts are prefabricated elements that are prepared in a factory for ease of install onsite. • Manufactured for IRC and IBC projects. • Examples: precut wood kits, engineered wood (glu-lam timber), metal building systems.
2D Open Panel	• Flat planar 2D wall, floor, and roof elements manufactured in a factory and installed onsite. • Does not include any enhancements or value add beyond the structural element. • May be sheathed on one side in light frame construction for ease and durability during picking and craning. • Supply for IRC and IBC projects. • Examples: light wood frame, light gauge steel, mass timber (CLT) panel.
2D Closed Panel (Enclosed construction)	• Flat planar 2D wall, floor, and roof elements manufactured in a factory and installed onsite. • Elements have variable value-added enhancements included such as insulation, windows/doors, water resistive barrier, vapor barrier, pre-wiring, plumbing, and cladding/siding. • High value subassembly that must be carefully transported and set onsite. • Supply IRC and IBC projects; a state jurisdiction may have a specific enclosed construction process for projects that employ construction that cannot be inspected onsite, often requiring a state or third-party inspector to visit the factory. • Examples: light wood frame, light gauge steel, structural insulated panels (SIPs), and mass timber (CLT) panel with value-add enhancements.
3D Volumetric Modular (Enclosed construction)	• 3D volumetric boxes manufactured in a factory and installed onsite. • The most complete degree of prefabrication elements including enhancements of insulation, windows/doors, water resistive barrier, vapor barrier, pre-wiring, plumbing, cladding/siding (less common). • High value subassembly that must be carefully transported and set onsite • More restrictive considerations for transport due to size of modules including special permits, lead cars, and time of day. • Supply IRC and IBC projects; a state jurisdiction may have a specific enclosed construction process for projects that employ construction that cannot be inspected onsite, often requiring a state or third-party inspector to visit the factory. • Examples: light wood frame, light gauge steel, hot rolled structural steel, mass timber (CLT) structured volumetric modules that are 50–90 percent complete in the factory prior to shipping.
3D Service Pod (Enclosed Construction)	• 3D bathroom and kitchen service pods and wet cores • Volumetric service pods and wet cores that are non-structural and integrate MEP to be used in multi-family, hospitality, and health care building types. • High value subassembly that must be carefully transported and set onsite (like millwork).

	• Supply IBC projects primarily; a state jurisdiction may have a specific enclosed construction process for projects that employ construction that cannot be inspected onsite, often requiring a state or third-party inspector to visit the factory. • Examples: light gauge steel kitchen wet core, prefabricated bathroom pod.
HUD Code (Enclosed Construction)	• "Manufactured home" built in a factory to 24 CFR Part 3280 administered by HUD. • Single-wide or double-wide section on permanent trailer chassis. • Minimum viable product as low-cost housing solution. • Zoning restrictions can apply depending on the jurisdiction. • HUD Code supersedes local building codes.

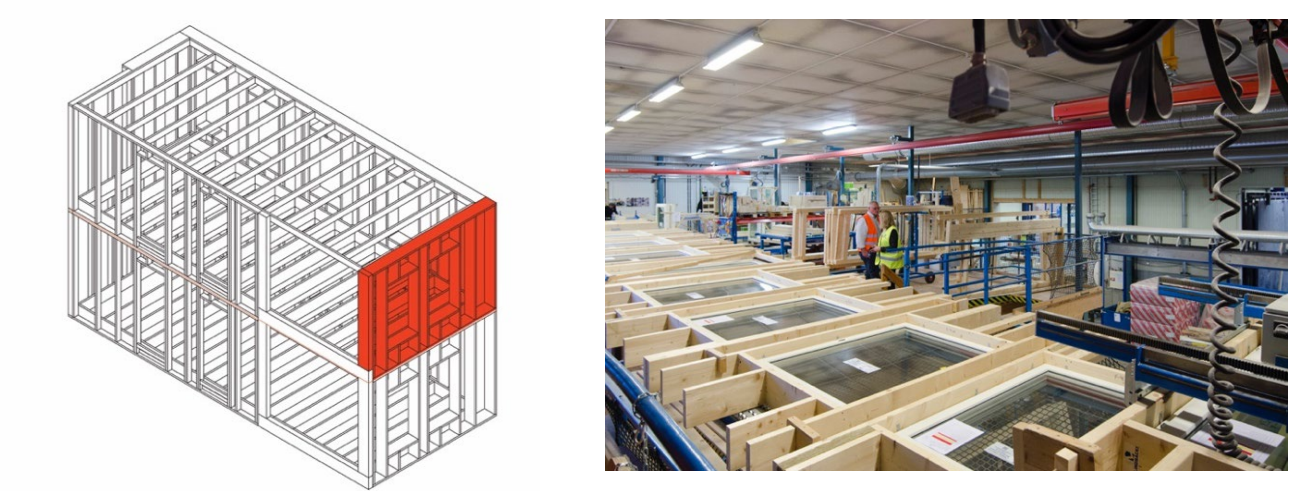
Source: MOD X

2.1.5 Degrees of Design Coordination: Predesigned, Project-Based, Designed for Manufacture and Assembly, Product Platform

Offsite construction requires significantly more design coordination than conventional construction to fully deliver on its promise of quality, speed, and economy. In the U.S. context, the HUD Code housing industry provides predesigned solutions or "models" that customers choose as variants. Some degree of predesign exists in volumetric modular, albeit models are often adjusted significantly. Volumetric modular manufacturers also support project-based design coordination. More coordination between design and the manufacturing and assembly process being used, aptly called *Design for Manufacturing and Assembly* or DfMA, is when a project team develops a design around the parameters of a particular offsite construction system or specific offsite construction company (Gao, Jin, and Lu, 2020; Lu et al., 2021). This approach is relatively rare, but it is increasing in use and has been driven by developers, GCs, architects, and engineers with experience in offsite construction.

The rarest approach to design coordination is the development of product platforms by offsite construction companies themselves. *Product platforms* require that the manufacturer and assembler develop a framework for balancing the needs of efficient manufacturing and construction with those of customization (exhibit 8) (Smith, 2019). The first step in developing a product platform is the *modularization* of a product and its related production processes into a set of subassemblies or modules (Schuh et al., 2017; Martin, n.d.). Buildings are not predesigned, but their potential subassemblies are, and they are then arranged or configured for the purpose of a particular project (Harland, Uddin, and Laudien, 2020). This approach has the potential to yield the greatest results from a manufacturing process, but it also requires significant upfront planning and constant assessment and improvement. This differs from the majority of current practices in offsite construction in the United States, in which projects are uniquely designed, manufactured, and assembled as customized panels and modules prior to onsite assembly. In this way, offsite construction in the United States is not fully taking full advantage of manufacturing principles and may be considered *prototype manufacturing* or *bespoke manufacturing*.

Exhibit 8. The product platform at Lindbacks Bygg in Sweden is the panel that can be reconfigured to make 3D volumetric modules prior to transporting and setting onsite. The panel in the 3D volumetric module highlighted (left) being manufactured (right).



Source: MOD X

2.1.6 Business Models and Business Platforms in Offsite Construction

The more systems integration that occurs in the factory, the more value is managed by the offsite subassembly manufacturer in the total cost of construction. As offsite construction can use a product platform approach, the more potential there is for consolidating, combining, and integrating the materials, products, services, and the value chain of housing delivery. Traditional construction relies on separate companies to develop, design, manufacture, and construct housing. *Vertical integration* combines services and products in a supply chain to provide greater end value (Perry, 1989). Internationally, companies in Sweden and Japan have found business success in vertically integrating portions or entire supply chain operations for offsite construction of housing into a *turnkey* delivery solution, whereby housing is delivered to the end developer or sold to the homebuyer ready for occupancy (Manley and Widén, 2019).

In the United States, companies are migrating *upstream* and *downstream* the supply chain to provide additional services and products in offsite construction. For example, offsite manufacturers can take on design and development services or onsite assembly services. Similarly, developers may become GCs for offsite construction projects specifically, and material manufacturers may move downstream and provide manufacture and supply subassemblies with their material products (Ku and Broadstone, 2017). Another business trend in the North American offsite construction for housing is *horizontal integration,* whereby one offsite manufacturer produces subassemblies for different markets. An example of this trend is a HUD Code manufacturer that also offers 2D panels or 3D volumetric modular subassemblies. In this way, manufacturers can use their capacity to achieve economies of scale and scope (Smith, 2019).

2.2 Research Roadmap Overview and Objectives

In 2020, HUD PD&R and NIBS discussed the possibility of developing a roadmap that could serve *both HUD and the offsite construction industry* in focusing research and development efforts on overcoming barriers to domestic offsite construction.

Three core objectives for the roadmap were identified by NIBS and HUD:

1. Identify the current state of knowledge concerning offsite construction for housing.
2. Identify the research areas, questions, and knowledge gaps in offsite construction for housing for the industry.
3. Disseminate the research needs to the industry, academia, and government.

The roadmap was structured and organized to be relevant to *all* elements of offsite construction for the housing industry, including single-family, multifamily, dormitory, supportive, affordable, and market-rate, and it is not solely focused on HUD Code housing. Although the Roadmap is designed to be mostly applicable to the residential sector, there are important elements of the roadmap that are relevant to removing industry-wide barriers in the commercial sectors, especially for hospitality development.

HUD has developed several research roadmaps to guide organizational learning during the past decade. Federal agencies now are required by law—the Foundations for Evidence-Based Policymaking Act of 2018—to develop learning agendas that align evidence-building activities with stakeholder-identified research priorities in support of evidence-based policy. Research roadmaps such as this one support such learning agendas by identifying research questions on focused topics through a well-structured consultation process. Technical topics such as offsite construction for housing especially benefit from such targeted consultation.

2.3 Research Roadmap Structure and Organization

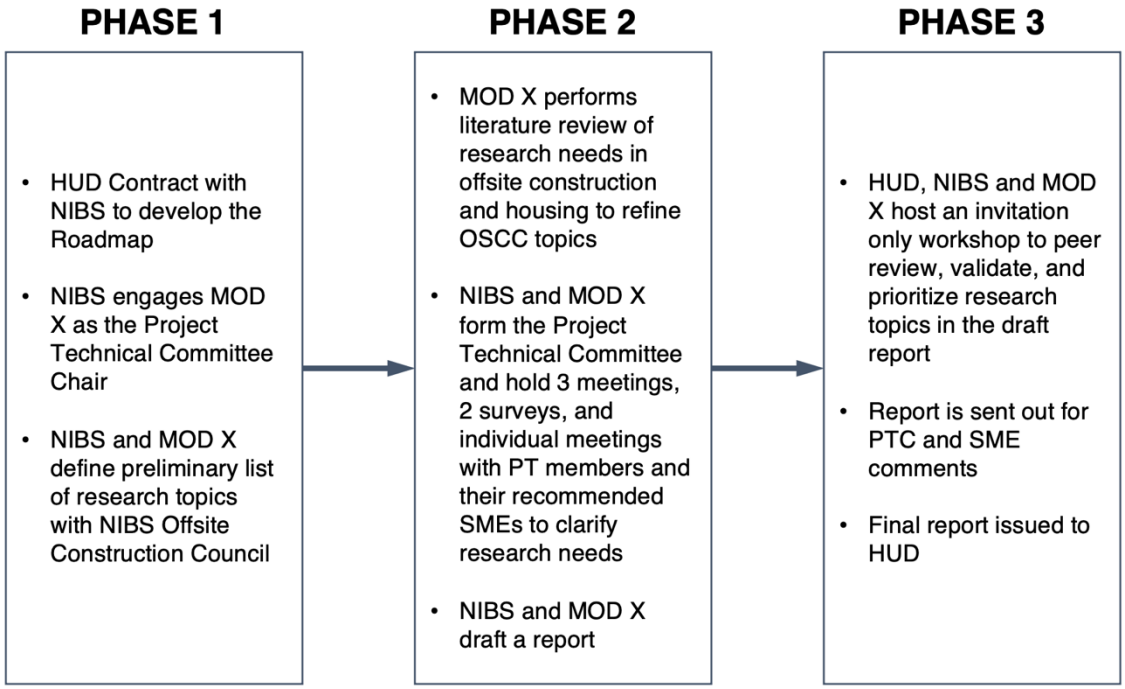
Given HUD's desire to focus the roadmap on the needs of the industry, NIBS decided to follow a report development structure that had been used successfully on previous projects. This approach included the following core activities (exhibit 9):

Phase 1—Contracting with HUD, engaging MOD X as the Project Technical Committee Chair, and developing a preliminary list of core research topics and questions with the NIBS Offsite Construction Council (OSCC).

Phase 2—Conducting a literature review to refine the preliminary list of research topics and forming a Project Technical Committee (PTC), a diverse group of leading experts from across the housing and offsite construction industry, to examine the research topics and questions.

Phase 3 - Holding an invitation only-workshop to review, validate, and prioritize the research questions. The PTC will comment on the draft report, finalize the roadmap, and submit it to HUD for publication.

Exhibit 9. Offsite Construction for Housing Research Roadmap Phases of Work Progression



Source: MOD X

2.3.1 Forming the Project Technical Committee

Following acceptance and award of the roadmap project to NIBS by HUD in June 2021, NIBS sought to form a PTC made up of a diverse group of academics and industry practitioners. NIBS selected MOD X, an industrialized construction research consultancy, to serve as the PTC Chair. NIBS then worked with MOD X to nominate distinguished members of the offsite construction community to serve on the PTC, based on criteria of diversity of professional background; experience; demographic and geographic representation; ability to clarify, critique, and develop new research topics; and how well-networked the members were for workshop participant invitations and workshop moderating duties. The initial list of 25 to 30 candidates eventually became 9 in total (exhibit 10).

Exhibit 10. Individuals Who Served as the Roadmap PTC

Name	Affiliation	Industry Expertise
PTC CHAIR: Ryan E. Smith	MOD X, Washington State University, School of Design and Construction	Research and Education
PTC CHAIR: Dr. Ivan Rupnik	MOD X, Northeastern University	
PTC CHAIR: Tyler Schmetterer	MOD X	Industry and Research
Tedd Benson	Bensonwood & Unity Homes	Manufacturing
Cindy Davis	State of Virginia; ICC President Board of Directors	Regulatory
Carol Galante	University of California, Berkley Terner Center for Housing	Research and Housing Consulting
Helena Lidelow	Lindbacks; Luleå University	Manufacturing
Sara Ann Logan	Volumetric Building Companies	Architect and Manufacturing
Cheryn Metzger	Pacific Northwest National Laboratory, DOE Advanced Building Construction Collaborative	Research
Lisa Podesto	Lendlease	Developer, GC
Justin Stewart	Synergy Modular / Synergy Inc.	Developer, GC
Margaret Whelan	Whelan Advisory	Investment

Source: Authors

The PTC was tasked with the following key activities:

- Meet with NIBS and the PTC Chair to determine the appropriate topics and research needs.
- Conduct literature reviews and identify gaps or additional areas of needed research to fulfill the broad objectives identified for offsite construction for housing.
- Participate in interviews with the PTC Chairs and fill out a qualitative survey to determine industry research needs.
- Attend and moderate breakout rooms during the stakeholder workshop and provide feedback on the draft roadmap report.

2.3.2 Drafting the Prioritized List of Research Needs

NIBS, MOD X, and the PTC met three times between September 2021 and November 2021. In addition, NIBS and the MOD X team met individually with each member of the PTC to discuss proposed research topics and questions in greater depth. NIBS, MOD X, and members of the PTC also held conversations with outside experts (as suggested by the PTC) to further refine and/or expand research needs. The resulting core topics, subtopics, and needs resulting from PTC and outside expert meetings included the following:

- Regulatory/Policy.
- Standards/Technical Performance.
- Finance/Insurance.
- Project Delivery/Contracts.
- Workforce/Labor.
- Business/Value Proposition.

2.3.3 Stakeholder Workshop

The PTC Chairs and PTC Members nominated approximately 70 candidates to invite to the workshop. These candidates were invited based on disciplinary diversity as follows: academic, research, codes, policy, finance, housing and offsite construction advocacy, development, design, engineering, manufacturing, and general contracting/construction management. More than 30 industry experts, representing a diversity of disciplines within the offsite construction industry, joined HUD, NIBS, MOD X, and the PTC to discuss the proposed research topics. Members of the PTC moderated breakout sessions during the workshop. NIBS and MOD X summarized the workshop discussions for inclusion in the final report. A detailed description of the workshop, and a full list of attendees, can be found in appendix A.

3 Research Topics Overview

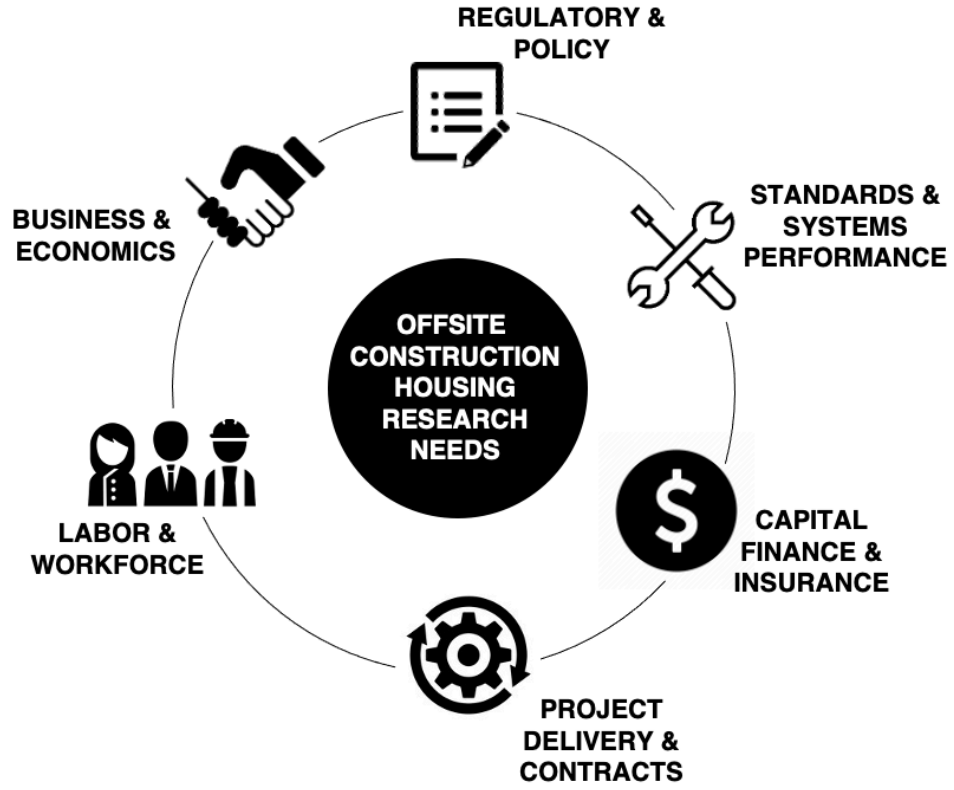
The HUD Offsite Construction for Housing Research Roadmap seeks to identify knowledge gaps in offsite construction in which research can help to develop and refine the supply chain to realize more affordable and accessible housing nationwide. Research can create new knowledge, clarify and codify existing knowledge, and communicate knowledge broadly. This report aims to identify research that can be produced in an offsite construction practice context at the nexus of researchers, industry stakeholders, and governments. The report also seeks to identify research topics that can lead to knowledge that is generalizable, intended to benefit the entire industry, and is not necessary to be commercially protected.

This report has been developed through a consensus process that reflects the perspectives of three groups: 1) The NIBS Offsite Construction Council, whose inputs defined the starting research topics; 2) The Research Roadmap Project Technical Committee; and 3) the Participants of the Research Roadmap Workshop. This process has been guided by the PTC Chairs, who have performed a literature review of barriers, challenges, and knowledge gaps in offsite construction, curated the consensus process with the PTC and workshop participants, and synthesized the perspectives into this report.

This consensus process has yielded six topic areas for offsite construction for housing research as shown in exhibit 11 and listed below:

- Research Topic 1: Regulatory Framework.
- Research Topic 2: Standards and System Performance.
- Research Topic 3: Capital, Finance, and Insurance.
- Research Topic 4: Project Delivery and Contracts.
- Research Topic 5: Labor and Workforce Training and Management.
- Research Topic 6: Business Models and Economic Performance.

Exhibit 11. Six Topics Identifying Research Needs in Offsite Construction for Housing During This Project



Source: MOD X

The choice of these topics reflects current challenges and opportunities in offsite construction. Although varied, all six topics reflect the interdisciplinary nature of offsite construction. For example, the Regulatory Framework topic touches on policy, whereas Finance and Capital deals with Business and Economic issues. This report does not directly deal with several important ongoing topics of research within the offsite construction sector, although each of the six topics has overlap with them. For reference, included below are three of the most widely researched areas that were not specifically addressed by the participants in this consensus process but are important to note in developing and fostering the offsite construction industry.

Offsite Construction Means and Methods

Offsite construction—including both means and methods—has been a topic of academic and industry research for the better part of the last century. This broad topic includes the technical processes specific to offsite construction: material and subassembly research, development, and testing; time, motion, and physical equipment and operations used in the factory; and new digital technologies and workflows that inform the planning and execution of offsite manufacturing and onsite productivity improvements and supply-chain management. Several academic institutions focus on the technical means and methods of offsite construction in the United States, including Penn State University, the University of Florida, Virginia Tech, Stanford University, Washington State University, Northeastern University, and many others. There is, however, still significantly

less focus on this topic when compared with universities in other countries. Furthermore, these institutions have focused more on providing an extension service to the industry, through technical testing and consulting, and less on basic research questions and development of new products and subassemblies for offsite construction specifically. In Canada, centers that are focused on offsite construction have been recently established in concert with government and industry at the University of Alberta, Industrialization of Building Construction, with an emphasis on Building Information Modeling and factory optimization, and the University of New Brunswick, Offsite Construction Research Centre, with means and methods of education and professional outreach.

In Japan, Sweden, Scotland, Switzerland, Austria, and more recently in South Korea, Australia, and New Zealand, strong offsite construction sector growth has been supported by academic research. In these contexts, industry-academic partnerships have generated some of the most important knowledge for moving the industry forward and achieving broader societal goals for sustainability and affordability in housing. For example, building science and offsite construction 2D panel research has grown simultaneously in the late 20th century in Sweden to necessitate aggressive governmental energy performance requirements (Perman, 2011). Some of these academia-industry-public sector partnerships have also included pilot programs that have compared the performance of various offsite and onsite construction systems. At the U.S. national level, one of the most important research projects in offsite construction means and methods has been the National Renewal Energy Laboratory's (NREL) "Integrating Energy Efficiency into the Permanent Modular Construction Industry," an excellent model for other university-government-industry collaborations (Pless et al., 2020) that has investigated energy efficiency technologies in offsite manufacturing.

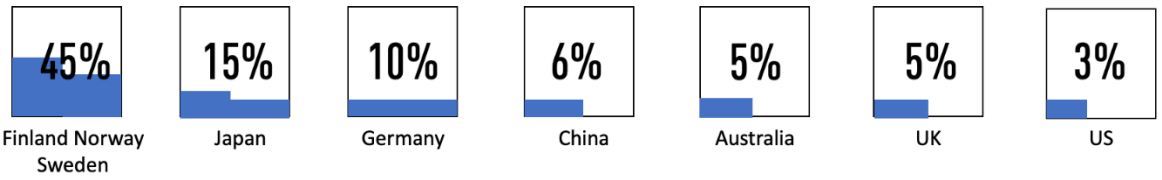
Offsite Construction Market Penetration and Performance

Accurately tracking the growth of offsite construction has been the focus of several trade associations and other entities over the last few decades in the United States. A lack of clear terminology and data culture has made assessing the growth of the industry a challenge. The most thorough data currently available, due to the unique HUD Code seal insignia program, cover the HUD Code housing industry only and are managed by the Manufactured Housing Institute (MHI). The Modular Building Institute (MBI) and the Modular Home Builders Association (MHBA) track some of the key data points of their members, most of whom are manufacturers who focus on permanent volumetric modular built to the IRC and IBC and relocatable structures. Some sporadic data is also available about other offsite construction systems, including open and enclosed panel from the National Association of Home Builders (NAHB) Building Systems Council, Structural Building Components Association (SBCA), and the Structural Insulated Panels Association (SIPA). Much of the data from these sources have been compiled by the Housing Innovation Alliance through their offsite construction heatmap (HIA, 2022). The significant growth in the use of panel systems by general contractors has not been adequately tracked and documented in the United States.

Industrywide reports attempting to assess market penetration of offsite construction have been prepared by FMI (2018), the McKinsey Global Institute (Barbosa et al., 2017; Bertram et al., 2019), Dodge Data & Analytics, Inc. (2020), Market Research Future (2021), Global Industry Analysts (2021), and Freedonia (2021), among others. These reports, however, are unclear about

the market definitions of open versus enclosed systems, panel versus modular, or HUD Code versus permanent, making it difficult to determine the accuracy or quality of the data. There are no standards for the collection and analysis of this data, and many of the reports are expensive and inaccessible. Conversely, in the European Union, a much more consistent system of tracking open access offsite construction value is in place, collected by Prodcom and analyzed and disseminated yearly by the European Construction Sector Observatory, a part of the Director General for Internal Market, Industry, Entrepreneurship, and SMEs (ESCO, 2022). Moreover, the Japan Prefabricated Construction Suppliers and Manufacturers Association systematically tracks all offsite construction and conventional construction in Japan, including the real estate value of offsite construction housing in single and multifamily homes as well as the number of modules produced per annum (JPCSMA, 2022).

Exhibit 12. Percentage of Offsite Construction for Housing Market Share by Country



Source: Adapted from McKinsey Global Institute

Social and Cultural Barriers to Offsite Construction Uptake

With its relatively long history in the United States, offsite construction has also been challenged by several social and cultural barriers to adoption and maturation—some that have little basis in fact and others that the industry brought upon itself. In 2007, HUD published a report on this topic titled "Factory-Built Construction and the American Homebuyer." This report captured a snapshot of the perception of offsite construction immediately preceding the global financial crisis amongst homeowners (Temkin et al., 2007). A report from NAHB (Holt, Benham, and Bigelow, 2015) and surveys from NIBS (2014, 2018) and MBI (Smith and Rupnik, 2018) confirm social and cultural challenges to offsite construction as voiced by construction industry professionals. Since that time, several internal and external factors have significantly changed the perception of offsite construction for housing.

During the Great Recession (2017–19), the new construction housing market shifted from single-family detached toward multifamily homes (HUD PD&R, 2021), requiring offsite manufacturers to look for alternative markets to supply. Since then, both single and multifamily construction has been on the rise nationally. Furthermore, finding available labor to meet the growing housing demand has continued to be challenging from postrecession to today in the construction sector. Also, increased energy efficiency and emissions reduction requirements by local and national building codes have builders seeking improved solutions for housing delivery (Storm, 2022). This trend has motivated developers and general contractors to look favorably on offsite construction methods and utilize them for housing projects as a potential solution to meet the growing need of housing concurrent with a lack of workforce. Most recently, a 2017 report on construction productivity by the McKinsey Global Institute and a follow-on report in 2020 on modular and offsite construction (Barbosa, et al., 2017; Bertram et al., 2019) have changed the perception of investors regarding offsite construction (and even popularized the term)

internationally. This has impacted the offsite construction for housing sector perceptions in the United States from financial institutions, investors, developers, designers, general contractors, and the public. Evidence of this change in perception is seen in publications by the American Institute of Architects (Wilson, 2019) and Fannie Mae (2020), among others.

Topics and Subtopics of Research in Offsite Construction (OC) Identified in HUD Offsite Construction Research Roadmap

The topics identified in this report are separated into the following topical sections:

3.1 Regulatory Framework.
3.2 Standards and System Performance.
3.3 Capital, Finance, and Insurance.
3.4 Project Delivery and Contracts.
3.5 Labor and Workforce Training and Management.
3.6 Business Models and Economic Performance.

Each topic section has an accompanying overview summary that describes the findings from the PTC and workshop meetings. The topical section then has subtopics listed with a narrative that indicates why the subtopic is important to addressing a barrier/challenge that research can help overcome or an opportunity/strength that research can support and develop further for offsite construction for housing. Finally, there are research questions listed under each subtopic to identify specific knowledge gaps for which further study, research, testing, and investigation are needed.

3.1 Research Topic 1: Regulatory Framework

With the ANSI industry consensus standard by ICC and MBI now available, it seems that HUD could streamline the manufactured home industry, remove unnecessary regulatory barriers, and increase consumer confidence by adopting these standards for all offsite construction. States could ease their workload with reliance on accredited third-party inspection and labeling organizations. Thus, you would have one simple set of construction rules (IRC and IBC) and a standard process (ICC/MBI) for offsite construction in all 50 states. This would create a level playing field and remove the patchwork of regulations that is holding the industry back from expanding.

- Cindy Davis, President Board of Directors, International Code Council

The regulatory framework that defines construction in the United States has evolved in response to *onsite* construction, thereby creating conditions that are often incompatible with *offsite* construction. One of the earliest attempts to remedy this legacy regulatory situation was initiated by HUD in the late 1960s as part of *Operation Breakthrough,* resulting in developing and instituting a unique building code that regulates manufactured housing, commonly referred to as the HUD Code. Most offsite construction methods, including kit-of-parts (1D prefabricated elements), panelized (2D prefabricated elements), and volumetric modular or modular (3D prefabricated elements), fall under two general building codes that include (1) the International

Residential Code (IRC) and (2) the International Building Code (IBC). *Authorities Having Jurisdiction* (AHJ), the local regulatory agency and authority, adopts the IRC and IBC in nearly all U.S. jurisdictions, as well as other ICC model codes (i.e., International Energy Conservation Code[4]). These codes are deemed *prescriptive*, specifying approved materials and assemblies rather than performance characteristics, and they have been developed to support a variety of site-built approaches.

Permitting and inspection of offsite construction is often onerous due to a misalignment between the mainstream approach to construction and the related building codes that are increasingly cited as an impediment to offsite construction adoption. The role of zoning and land use regulations as they relate to offsite construction is also increasingly noted as a barrier to offsite construction implementation. More highly enhanced prefabricated components utilized in panelized and volumetric construction (i.e., enclosed sections) are considerably constrained by a variety of state-specific transportation regulations due to load size (length, width, and height) and weight requirements.

The NIBS OSCC, PTC, and workshop participants overwhelmingly identified the design review, permitting, and inspection process as a major obstacle to the adoption and implementation of offsite construction and a key topic for additional research. Despite nearly 50 years of development and practice related to the permitting and inspection process of offsite construction, the current approach remains fundamentally informed by the context and reasoning of onsite construction. Several project examples illustrated by the participants involved an AHJ not being familiar with offsite construction and/or the regulatory framework that supports offsite construction, subsequently leading to significant delays, budget ramifications, and other major issues.

Roadmap participant aspirational goals included fully revising the permitting and inspection process of offsite construction systems and components similar to other manufacturing industries, particularly the automotive industry. The permitting and inspection of the HUD Code-regulated industry was also discussed as a potential research topic and source for insight regarding how to reform the process for other offsite construction systems. By virtue of the global representation of the PTC and the workshop group, several proven international models were discussed that offer solutions to the systemic U.S. offsite construction industry regulatory issues. The notion of a HUD-supported national AHJ education program in offsite construction was discussed as a potentially impactful solution.

Third-party inspections were discussed as a topic of additional research in terms of the effectiveness of the established process in relation to the additional cost compared to

[4] The International Council of Codes (ICC) is a non-government for profit organization that produces model codes and standards for building safety. ICC uses a consensus process with industry stakeholders to develop and refine its model codes in 3-year cycles. In the United States, regulations for building construction are the responsibility of the Authority Having Jurisdiction (AHJ) at the state, county, or municipal level. Therefore, AHJs adopt the ICC model codes as their own but may apply certain additional regulations as well. The International Building Code (IBC) and the International Residential Code (IRC) are the most adopted construction model codes by AHJs nationally. Furthermore, the International Energy Conservation Code is also often adopted by AHJs for energy performance criteria.

conventional construction. Technology supporting better design review, permitting, and *remote virtual inspection* (RVI) was also seen as a relevant topic of further research.

During the PTC sessions and subsequent workshop, participants with experience in international offsite construction discussed the measurable impact of *performance-based* codes on overall market development in comparison with the *prescriptive-based* codes employed in the U.S. offsite construction industry as a relevant research topic. In the European Union (EU), performance-based codes have been successfully implemented to unify a highly heterogenous set of building cultures and technologies while encouraging competition and the free exchange of ideas for several decades. In Japan, similar market results were achieved from a gradual transition from prescriptive to performance-based codes (Matsumura et al., 2018; Tomohiro, 2013). During the workshop discussion, further investigation into this topic for similar reasons was reinforced.

Group interest in researching the potential benefits and challenges of adopting an *offsite construction-based* code, similar to the HUD Code, was discussed during the PTC sessions and workshop. Many participants expressed concern, however, that this would not necessarily present a solution to removing obstacles to offsite construction penetration and may reinforce certain negative traits inside and outside of the industry. Furthermore, the participants from countries outside the United States indicated that there has not been a need for a new offsite construction code abroad, but rather a set of standards or guidelines that indicate how offsite construction housing projects are permitted and inspected and a movement toward performance-based codes. Finally, ICC notes that although performance-based codes are legally acceptable, they are rarely used, and the council is actively trying to determine how to encourage their use in order to foster innovation and construction productivity (ICC, 2018).

Several state and municipal initiatives have proven successful in nurturing the growth of offsite construction and achieving the promise of more equitable, sustainable, economical, and higher quality and performance housing. Participants agreed that these individual initiatives should be compiled and assessed to extract valuable industry best practices that can be clearly communicated and made readily available across the country.

In addition to the building codes governing the offsite construction industry, additional research into the impact of existing zoning ordinances and policies was encouraged. Various participants provided successful examples of zoning variances for encouraging the use of offsite construction. For instance, in California, the Oakland Construction Innovation and Expanded Housing Options Ordinance was enacted to address local building costs and housing affordability, and it includes provisions to "allow occupancy of RVs and tiny homes on wheels on private property subject to certain health and safety standards, allow mobile homes and manufactured homes (HUD Code) in all zoning districts where residential uses are permitted, establish density and open space regulations for efficiency dwelling units, and to establish height regulations for modular construction" (Oakland, 2021). The final provision regarding "modular," or more precisely permanent volumetric modular construction, adjusts the maximum height of overall building structures in certain land use zones to allow for this form of construction. This was needed because volumetric modular construction requires increased dimensions of floor-to-floor heights due to the aggregation of the ceiling and floor structure of stacking modules. This

builds upon several regulatory framework modifications in California, including some that have encouraged the use of accessory dwelling units (ADUs) as an effective tool to address suburban densification.

Several standards for offsite construction are being developed by ICC in partnership with the Modular Building Institute and ANSI.[5] These standards include the ICC/MBI 1200 Standard for Offsite Construction: Planning, Design, Fabrication and Assembly; ICC G5-2019 Guideline for the Safe Use of ISO Intermodal Shipping Containers Repurposed as Buildings and Building Components; ICC/MBI Standard 1205: Standard for Offsite Construction: Inspection and Regulatory Compliance; and ICC/MBI Standard 1210: Standard for Mechanical, Electrical, Plumbing Systems, Energy Efficiency and Water Conservation in Offsite Construction. Additionally, the Specialized Carriers and Rigging Association (SC&RA) is developing the UPT 2021: Uniform Permit Transport 2021 to harmonize all 50 states for oversized and overweight transport. However, due to the recent publication of these documents, it is unclear if the standards are being adopted and how effective they are at improving offsite construction project delivery outcomes.

Included below are regulatory framework research subtopics developed by the NIBS OSCC, PTC, and workshop participants. The research subtopic is named; the challenge, barrier, or opportunity is described, and then related research questions are listed.

Regulatory Frameworks Research Subtopics

Quantify the challenges of offsite construction for AHJ permit and inspection processes. The U.S. model of local AHJ for permit approval and inspection is problematic for offsite construction because the AHJ may be unfamiliar with or biased against offsite construction. Although there is an ICC code that is updated every 3 years, the local AHJ adopts a version of the code and then determines how often it will update. Further, the AHJ has the authority to interpret the code during permitting and inspection. Therefore, code officials at the local level have the legal authority to accept or reject the application of any new product or system innovation, and this engrained culture has challenged building product innovation in the United States for decades (Oster and Quigley, 1977). Although this obstacle to offsite construction is implicitly understood in the industry, the extent and significance of AHJ roadblocks are unknown. Finally, pathways to overcome AHJ barriers have not been researched or documented.

Related Research Questions

- What are the quantified and qualified challenges of the AHJ permit and inspection process on offsite construction?
- To what extent does the AHJ present a roadblock or ease the use of offsite construction?
- How can these barriers be overcome?

[5] The Modular Building Institute is a U.S.-based, internationally reaching nonprofit trade association for volumetric modular commercial construction. ANSI is the American National Standards Institute, a private nonprofit that oversees the development of voluntary consensus standards for products, services, processes, systems, and personnel in the United States.

- How can successful cases of offsite construction and AHJs interfaces be collected, codified, and transferred to other AHJs?

Determine the impact of third-party inspection on project delivery performance.
Due to the enclosed nature of offsite construction enclosed subassemblies, much of the inspection work is completed in the factory, often by a third-party certified inspector that reports to the AHJ, who also inspects the site work and onsite assembly. This requires additional coordination and communication, and often miscommunication, between the third-party inspector and the AHJ. Scope delineations between what is inspected in the factory and what is inspected onsite require changes in drawing conventions and can create situations of double handling, inspection gaps, schedule delays, and in some cases rework. This impact needs to be assessed, and solutions to overcome third-party inspection obstacles need to be researched. Additional information related to the ICC third-party inspection process for offsite construction is provided by the ICC FAQs on Offsite Construction document (ICC, 2020).

Related Research Questions

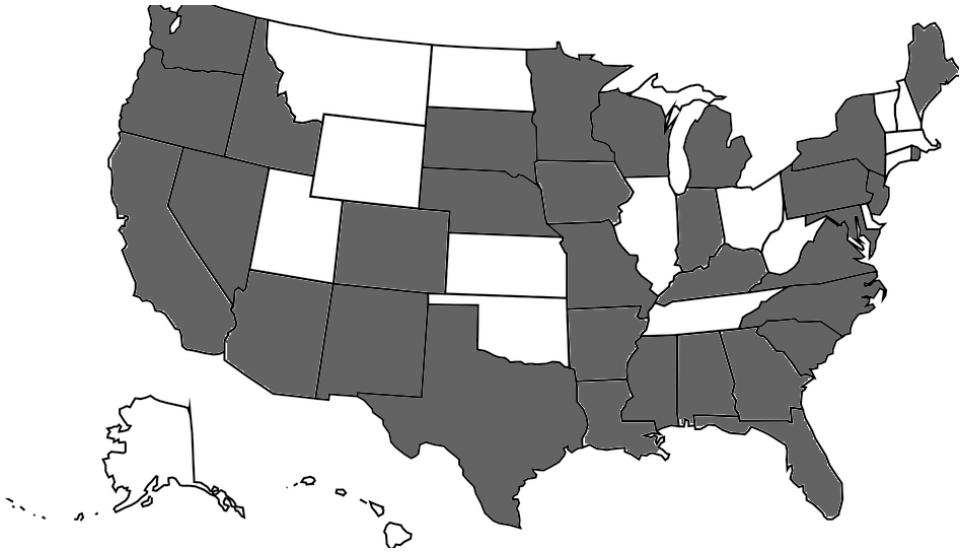
- How do third-party inspections impact the cost and schedule of offsite construction for housing?
- What miscommunications most often occur between the AHJ and third-party inspectors?
- What scope challenges between the AHJ and third-party inspection does offsite construction for housing face?
- How can third-party inspection coordination be improved?

Assess the effectiveness of state enclosed or modular regulations for offsite construction uptake and project delivery performance.
Not all AHJs have jurisdiction over offsite construction. Some states (35 of the 50) have their own enclosed or modular requirement process (MBI, 2022) for subassemblies that need to be factory-inspected due to structural or service systems that are embedded and not visible when setting onsite (exhibit 13). This may be conflated with or separate from the HUD Code. In this situation, there can be coordination conflicts between the scope of responsibility of the AHJ and the state agency or office that oversees offsite construction, resulting in communication gaps and schedule delays. The impact of this disconnection between the state enclosed construction regulations and the AHJ needs to be further assessed, and mitigation efforts need to be developed.

Related Research Questions

- How effective are state enclosed and modular regulations in fostering offsite construction use?
- What coordination and communication conflicts most often occur between the AHJ and state agency with enclosed or modular construction oversight?
- What are the measured impacts of this disconnection between AHJs and state enclosed construction agencies?
- How can AHJ and state enclosed construction coordination be improved?

Exhibit 13. States That Have an Enclosed and Modular Home Code (35 of the 50)



Source: MOD X

Evaluate the technical, social, and cultural barriers to remote virtual inspection (RVI) for offsite construction.

Technology-enabled remote inspections, or remote virtual inspection (RVI), are advancing in onsite construction with the potential to reduce inspection time and labor. Although this is just beginning to be used and seemingly would be of great benefit to offsite construction, there are reported technical challenges with remote inspection due to camera set-up, WIFI connections, training, and production-line access (ICC NTA, 2020). There are also social and cultural barriers of AHJs and/or offsite construction manufacturers that are not familiar with RVI procedures and the enabling technologies. However, there is also the opportunity to design offsite manufacturing facilities considering RVI at the outset. Research is needed to evaluate the barriers and opportunities associated with remote inspection for offsite construction. Many of the same challenges associated with scope coordination of inspecting in the factory and site apply to remote inspection as well.

Related Research Questions

- What are the technical barriers and benefits of RVI for offsite construction?
- What are the social and cultural barriers to RVI for manufacturers and AHJs?
- What coordination and communication challenges and opportunities of RVI for offsite construction?
- How can these challenges be improved?
- How can best practices be collected and transferred to housing and offsite construction stakeholders, and AHJs?

Compare regulatory frameworks and offsite construction in more mature international markets.

There are several international offsite construction industries that are significantly more developed than the U.S. industry by market penetration, including those in Japan, Sweden, and central Europe (Bertram et al., 2019). The particulars of the regulatory frameworks in these countries are not well understood from a historical, procedural, and transferability perspective. Literature review shows that regulatory changes did have an impact on market uptake and evolution of offsite construction in Sweden through the Million Homes Program (1960s and 1970s), Sweden's version of Operation Breakthrough, and subsequent code changes (BBR 94) that allowed for wood-based building to eight stories (Lundgren, 2016; Lidelow, 2017; Hall and Vidén, 2006; Lessing, 2006) that helped transform the enclosed panel industry to double-digit growth in the 1990s and 2000s. Likewise, in Japan, the Ministry of Housing, along with a prefabrication trade association, have continuously advanced offsite construction for housing since the 1970s through a factory certification process (Matsumura, 2004, 2006; Buntrock, 2017; Hall, 2008). In addition, Australia has quickly become an international leader in high-rise 3D volumetric construction and has developed a unique offsite construction country standard to accommodate this market growth called the "Handbook for the Design of Modular Structures" (MCCB, 2017) that, like the ICC/MBI standards, outlines project delivery processes and harmonizes residential offsite project delivery with the Australian Building Codes. Additional research is required to determine what can be learned from these international key lessons and applied to the U.S. offsite construction for housing regulatory process.

Related Research Questions

- How is offsite construction regulated in more evolved international markets?
- What benefits and challenges have international offsite construction industries faced in offsite construction regulatory progress?
- What lessons can be transferred and tested in the U.S. offsite construction for housing industry?

Research performance-based codes internationally and test performance-based codes in the U.S. offsite construction industry.

The U.S. building ICC codes, including the IRC and IBC, were established on a prescriptive model of construction including building type, construction type, occupancy type, and particular building materials assemblies that are preapproved to achieve these requirements. Alternatively, performance-based codes set out an operational requirement (i.e., energy performance[6], acoustical performance, fire performance, structural performance) without prescribing the material assemblies that can satisfy that standard (Eisenberg, Done, and Ishida, 2002). Performance specifications have empirically fostered innovation and competition in international construction markets and other industries (Foliente, 2000; Tomohiro, 2013). Performance codes require additional simulation or physical testing to demonstrate compliance with performance

[6] The International Energy Conservation Code (IECC/ASHRAE) performance pathway provides offers provisions for demonstrating energy compliance using simulation of the design project instead of prescriptive descriptions of materials and assemblies. Prescriptive energy codes depend on calculations of conduction (R-Value or U-Factors), however in performance code compliance, simulation of convection for air infiltration and exfiltration are considered for overall performance. Offsite construction is theoretically able to achieve greater performance but is challenging due to the factory to site technical coordination of the envelope systems to achieve the simulated performance goals including transport and handling damage that can compromise the envelope, and panel-to-panel or module to module connections onsite and maintaining exterior continuous insulation, for example.

specifications. Although the U.S. ICC has a performance-based code pathway, it is underutilized due to the time-consuming and cost-prohibitive process with which participants must engage to demonstrate compliance, subsequently resulting in most projects utilizing a prescriptive method by default. The offsite construction and performance-based code lessons from international countries need to be researched, evaluated, and tested in the U.S. offsite construction context. Exhibit 14 compares prescriptive codes to performance codes. Additional information is related to the ICC Performance Code (ICC, 2018).

Exhibit 14. Prescriptive Versus Performance-Based Codes Characteristics

Prescriptive Codes	Performance Codes
Outlines exact specifications and construction standards	Describes expected results
Less flexible	Flexibility regarding achievement of results
Stifles innovation	Cost efficiencies and optimization
Lacks incentive for change	Value add innovation
Proven methods	Design driven
Less individual design	References other standards through testing/compliance of performance

Source: MOD X (Adapted from Foliente, 2000)

Related Research Questions

- How does the prevalent prescriptive IRC and IBC code limit offsite construction progress?
- What are the defining features of performance-based codes internationally?
- Why are performance codes and specifications not used in the United States?
- How do performance-based codes foster innovation and offsite construction uptake internationally?
- What are the obstacles to developing and using performance-based codes abroad and in the United States?

Evaluate the benefits and challenges of improving the HUD Code.
Current housing construction in the United States, except for HUD Code, must comply with the IRC or IBC prescriptive or performance-based codes. The HUD Code for Manufactured Home Construction and Safety Standards applies to homes that are built and remain on a chassis for the duration of their lives. This is a building code that represents a prescriptive standard that is less restrictive than the IRC or the IBC and does not follow a similar 3-year update review. Efforts by HUD during the 1970s fostered growth from a fledgling trailer home industry into a national federal code and transformed the HUD Code industry in the following decades to a considerable market share of single-family housing today (10 percent).

Related Research Questions

- What was the process by which the HUD Code transformed the historic trailer home industry?
- How can the HUD Code be updated and improved in a regular cycle like the IRC and IBC?

- What are the cost and housing market implications of improving HUD Code manufacturing standards to be more durable and higher energy performing?
- What are the benefits and challenges of increasing the prescriptive or performance standards for HUD Code housing?

Investigate the impact of U.S. state and municipal initiatives to foster offsite construction for housing by overcoming regulatory framework barriers (e.g., entitlements, land access and cost, zoning, patient capital and start-up investment, impact fees).
There have been case studies nationally of government initiatives enacted to foster offsite construction for housing through several strategies and tactics. Although some of these initiatives include public relations designed to encourage developers to employ offsite construction methods, others have been more institutionalized. For instance, some jurisdictions have removed language from land-use codes that limits the implementation of offsite construction, and others have revised exclusionary zoning to encourage a variety of housing types. Governments have instituted processes for expediting the entitlement and plan-review timeline and reducing the impact fee requirements for offsite construction for housing projects to encourage more access and affordability to housing solutions for their cities. In addition, there are ideas being shared about governments providing offsite construction project loan programs and incentives for factory start-ups to stimulate the offsite construction housing industry in their respective regions. The impact of these potentials initiatives is relatively unknown, and best practices have not been compiled and disseminated widely.

Related Research Questions

- What are the tested case study examples of local government initiatives to foster offsite construction?
- How effective have each of these initiatives been in fostering offsite manufacturer capacity and offsite construction uptake?
- How can these lessons be collected, analyzed, improved, and shared with other states and municipalities?
- What are other untested ideas could be implemented and analyzed for local government initiatives to promote, and remove barriers to, offsite construction? How might these research tests be implemented, and how might data be gathered?

Study the impact of the American Disabilities Act (ADA) and interpretation by the AHJ on offsite construction.
The American Disabilities Act (ADA) requires housing to comply with design and construction standards that accommodate different abilities. Offsite construction for multifamily housing ideally develops a set of product standards that can be adaptively reused from one project to another to take advantage of repetitive manufacturing. Flexible design changes to these manufacturing platforms reduce the value of factory-based production for multi-family housing. Some stakeholders have decided to employ an ADA standard design for all their offsite construction for housing products and projects, but this potentially creates downstream cost implications for production. The trade-off between standardizing product platforms for ADA and the added cost of producing ADA-compliant housing is currently unknown and needs to be investigated. Furthermore, the AHJ interpretation of ADA and how it is inspected and verified in offsite construction (factory versus jobsite) is inconsistent and warrants further study.

Related Research Questions

- How do offsite manufacturers address ADA for multifamily housing product platform development?
- What are the cost and schedule impacts of ADA for offsite construction in multifamily housing development?
- How is ADA interpreted differently by AHJs, and how does that difference impact offsite construction?
- What are the trade-offs between an ADA standardized unit versus the added cost of ADA compliance?

Review the effectiveness of the recent ICC offsite construction standards on overall project value for the offsite construction industry.

The ICC recently developed several standards for offsite construction, including ICC/MBI 1200, ICC/MBI Standard 1205, ICC/MBI Standard 1210, and ICC G5-2019. The standards are intended to be a guide for stakeholders and AHJs in the project delivery, mechanical/electrical/plumbing (MEP) services, use of shipping containers in construction, and regulatory review and inspection process for offsite construction. However, due to the relatively recent publication of these documents, and some not issued or officially released at the time of the writing of this report, it is unclear if the standards are being adopted, and it is unclear how effective they are at improving offsite construction project delivery outcomes. Although this is a positive step showing initial signs of success (i.e., IC/MBI 1205 was adopted in Salt Lake City AHJ), these standards need to be reviewed and continuously improved (ICC, 2022).

Related Research Questions

- To what extent are the ICC/MBI Offsite Construction Standards being implemented nationally?
- How are the ICC/MBI Offsite Construction Standards being disseminated and adopted/implemented by AHJs?
- How effective are the new standards in improving project delivery performance and uptake of offsite construction?
- How can the concerns of AHJs that are considering the standards be shared publicly and discussed?
- What are ways that the lessons learned from AHJs that are adopting the standards be collected and shared across the United States for continuous improvement?

Determine the impact of current transportation regulation by state on offsite construction.

The U.S. transportation codes are currently regulated at the state level. This means that offsite construction subassemblies that are manufactured in one state but trucked across state lines for onsite assembly may have different requirements for permitting transportation, lead times and costs, allowable times of day for transport, escort car rules, etc. Furthermore, states may enforce different requirements on dimensions, weight, and carrier connections of offsite construction product freight that can impact the design, manufacture, project assembly, and the associated cost of offsite construction for housing. The impact of these transportation regulations by state, the impact of an emerging national transportation code for oversized or overweight freight (SC&RA, 2021), and best practices in transportation for offsite construction for housing require additional research.

Related Research Questions

- How do the different state departments of transportation regulations compare in their standards and the way in which they are enforced?
- What are the impacts of differing state transportation regulations on offsite construction for housing cost and schedule?
- What is the current and future impact of the emerging national transportation standard UPT2021 on offsite construction for housing?
- How can the lessons learned from the early use of this national transportation code be collected and shared to benefit the U.S. offsite construction industry?

3.2 Research Topic 2: Standards and System Performance

The US's current regulatory and inspection processes force offsite companies to take a lot of risk and R&D costs up-front. We do our own testing, and invest more in unique engineered IP than we would otherwise do, as compared to our peers in other countries where the regulatory framework is more conducive to offsite. This in turn makes us have to devote more focus and attention to the formal protection of IP more rigorously, in order to make a long-term return on our increased early investment.

– Rebeca Lorenz, Assembly OSM

The Code Compliance Research Report process wasn't intended for multifaceted components or a system of products that can be used together in a sub-assembly. Using it for this is like putting a square peg in a round hole. The industrialized off-site industry needs a code compliance verification system that is robust enough to demonstrate code equivalent performance, flexible enough to address a complete building system platform and nimble enough to adapt with each generation of product improvement.

- Lisa Podesto, Lend Lease

The previous section on regulatory frameworks explained how regulations and codes can be a significant barrier to the adoption and growth of offsite construction for housing. Codes are regulations by which builders construct housing, and they are adopted and enforced by the AHJ at the state, municipal, or county level. This section outlines a topic related to regulations that needs to be addressed for offsite construction for housing to progress: standards and system performance. Standards are developed where there is a lack of information or specificity in a code, and they are often referenced within building codes. Standards organizations, including ANSI, ASTM, UL, ISO[7], and others, use a consensus process of stakeholders to determine a

[7] ANSI = American National Standards Institute; ASTM = American Society for Testing Materials; UL = Underwriters Laboratories; ISO = International Standards Organization.

commonly agreed upon practice, product specification, personnel operation, or other concern. Standards for products often include considerable testing to demonstrate technical compliance with codes. For example, the ICC/ Modular Building Institute 1200, 1205, and 1210 are standards for offsite construction that are written to be in support of and harmonized with the ICC family of codes and standards, including IRC and IBC.

Guidelines are not codes or standards. They are educational resources and tools to help stakeholders employ best practices to support added safety and project success. Guidelines, such as the G5-2019 Guideline for the Safe Use of ISO Intermodal Shipping Containers, are written to provide AHJs with the questions they should be asking about offsite construction methods. Guidelines often precede standards and codes to address emerging products and practices that may not be developed in a 3-year code cycle, or the AHJ may not adopt a new code for two or three code cycles (6 to 9 years).

One of the most frequent obstacles to construction productivity is a lack of common practices and feedback systems that link industry standards and a regulatory framework with individual company innovation. In mature international offsite construction industries, the development of a clear and evolving set of guidelines and standards has significantly increased offsite construction penetration and productivity performance. This is because standards can reduce risk while fostering a competitive and innovative industry culture.

A discussion involving the current testing process of materials and assemblies, as related to ICC compliance, was closely linked to the PTC and workshop participant discussions involving the permitting and inspection process of offsite construction and the impact of performance-based codes. The current ICC Evaluation Service (ES) process and associated cost and time were noted as significant hindrances to fostering innovation, standardization, and competitiveness within the housing industry. The current process was also described as a deterrent to developing a functional research and development (R&D) culture that has been the hallmark of other successful manufacturing industries. Additional research into creative knowledge transfers from alternative industries within the United States and from mature international offsite construction for housing industries was highly encouraged. Participants also identified the challenge of disconnects between standards testing laboratory interests and motivations and industry research and development needs as an obstacle to an innovation ecosystem for housing.

In the U.S. context, HUD’s decision to provide better industry standards to the existing trailer home industry in the 1970s that became the HUD Code directly resulted in the growth of the market and increased access to affordable housing for a large segment of the population. At the same time, the lack of a vital feedback loop between individual companies, industry standards, and the overall regulatory framework for HUD Code, with no continuous improvement, has stifled the continued growth of this offsite construction segment. The HUD Code housing industry has acknowledged this critical requirement, has attempted to rectify the situation with more frequent updates, and is considering how to improve offsite construction for this housing type.

Supply-chain disruptions can significantly impact housing affordability. Offsite construction is not different from traditional construction in this respect. It was noted in meetings with experts

that the quality of lumber supply for offsite construction was an obstacle to achieving the tighter tolerances required for factory production and providing a structure for follow-on systems (i.e., insulation, finishes, cladding, etc.), especially when utilizing automation and robotics in manufacturing. Participants, however, pointed out that offsite construction has demonstrated and has the increasing potential to develop standards that can foster more reliability and redundancy in the material supply chain. This is because offsite construction can predict the specific manufactured subassemblies and their role in projects as it relates to factory flow. One way that participants suggested that this is starting to be accomplished is through the development of product platforms.

Not all housing types and markets benefit from the significant investment of a product platform that an optimized supply chain and production process requires. An affordable or attainable multi-family housing platform, however, could potentially be a standard for the offsite construction industry. This has been successful in Canada through the BC Housing and Vancouver Affordable Housing Agency's Rapid Housing Initiative (BC Housing, 2021), which is now being implemented in the City of Toronto to deliver thousands of units of housing through a product platform approach. Furthermore, according to offsite manufacturers on the PTC, the offsite construction industry could benefit from dimensional standards that can inform material manufacturing and supply.

Regarding system performance, participants from the offsite construction industry explained that clients and regulations are requiring a more aggressive response to environmental sustainability, just as with traditional construction. This growing demand is not only in operational performance, but also in construction performance—the embodied energy and carbon in the materials, products, and subassemblies used in offsite construction for housing. Offsite construction conceptually is able to achieve an increase in energy performance due to the quality control and quality assurance processes of factory production, but transporting and handling subassemblies to sites and installation can jeopardize product performance due to damage. Participants commented on some of their own experiences with the misalignment of designed energy performance and post-occupancy performance of offsite constructed housing projects and noted several technical and communication barriers. Lower carbon materials and materials that do not create poor indoor air quality concerns are improving at a rapid pace, and offsite manufacturers are being asked to provide more evidence of meeting these goals through documentation and, in some cases, *environmental product declarations* (EPDs).

Standards and System Performance Research Subtopics

Develop a common terminology for offsite construction that can be shared across the academic and industry sectors.

Although there are several sources for U.S. offsite construction for housing terminology, including the NIBS Glossary (NIBS, 2015), ICC Offsite Construction Toolkits (ICC, 2020), and Offsite Architecture (Smith and Quale, 2017), there is no universally accepted common language concerning offsite construction. HUD has used the terms *industrialized housing*, *factory-built housing,* and, most recently, *offsite construction* to describe moving operations from the jobsite to a factory environment and applying modern manufacturing approaches to production. Terms, and understanding of their meanings and definitions, are a result of the individual experience of

professionals and academics, with the former using terms for getting the work done at the present and the latter for categorization and clarifying for the improvement of the industry in the future. Furthermore, definitions vary from region to region in the United States and internationally, indicative of the geographic context and etymology (e.g., builders in Japan refer to 3D volumetric *units*, those in Sweden refer to volumetric *boxes,* and those in the U.S. refer to volumetric *modules* or *modular)* (Smith, 2016; Bertram et al., 2019; Hairstans, 2015). There is a real cost associated with a lack of common terminology as the offsite construction for housing industry grows and becomes more ubiquitous nationally. The authors of this report have outlined some key terminology that emerged during the PTC meetings, workshop, and literature review that are intended to help clarify this report (see Introduction and Section 2.1—Key Offsite Construction Concepts). Although terms and definitions will continue to evolve with practice, there is a need for a process to codify, review, and continuously refine terminology into the future.

Related Research Questions

- What is a consensus process that can be used to codify, review, and continuously refine terminology for the offsite construction industry?
- How can common terms, definitions, and meanings be communicated and shared with critical stakeholders that are new to offsite construction, such as AHJs and developers?

Determine the extent to which material testing and ICC compliance are inhibitors for innovation in the offsite construction industry.

The ICC-ES (2022) provides reports that are the most preferred resource used by code officials to verify that new and innovative building products comply with code requirements. The ICC-ES provides information about what code requirements or acceptance criteria were used to evaluate the product, how the product should be installed to meet the requirements, how to identify the product, etc. ICC-ES reports also require evidence through testing from an ICC-certified standards laboratory (i.e., ANSI, ASTM, UL, etc.) and how the product complies or is a suitable alternative to the requirements of the applicable code. Obtaining an ICC-ES Report is a process that is both time-consuming and expensive, and participants report that it does not foster innovation or competitiveness for small businesses and inventors, and it further reinforces prescriptive specifications. The ICC-ES process has encountered difficulty accommodating larger subassemblies (i.e., 2D enclosed panels or 3D volumetric modular) in offsite construction that integrate various material products for performance outcomes. The extent to which the current ICC-ES process is an obstacle to offsite construction and small business innovation needs to be researched. Additional information related to ICC-ES reports is available at the following website: https://icc-es.org/

Related Research Questions

- What are the scope, time, and cost impacts on new product development for offsite construction using the ICC-ES process?
- How are these impacts a barrier to innovation and new market entrants and start-ups? How can these barriers be overcome?
- What is a pathway for offsite manufacturers of subassemblies that aggregate existing laboratory-certified products to develop ICC-ES reports?

- What is a potential alternative to ICC-ES for offsite manufacturers to demonstrate compliance and improve speed to market for new products and subassemblies?
- What is intellectual property, and what is generalizable knowledge in offsite construction products and processes?

Develop relationships between industry and research laboratories in technical testing and research for offsite construction.
Technical testing is needed at certified laboratories to establish ICC-ES reports to verify compliance with prescriptive or performance-based codes. The offsite construction housing manufacturers and general contractors for projects require technical lab testing for new subassemblies. Material manufacturers and suppliers also require lab testing to verify adequacy performance. Although some of these requirements are being met by research laboratories at universities, nationally certified labs (i.e., NREL and PNNL), and private certified labs (Home Innovation Research Labs), the labs are also seeking additional research projects through responses to federal grant RFPs. This can lead to a disconnect between what industry requests and what research labs are proposing. There is a need for a more established innovation culture for new materials, products, and subassemblies for offsite construction and partnerships between industry, government, universities, testing labs, and national labs to address this gap.

Related Research Questions

- What are the common shared technical testing needs of the offsite construction industry that can be generalizable for research laboratories to provide?
- What are the capabilities, interests, and motivations of research testing laboratories at public and private institutions nationally?
- What are the disconnected gaps between what the offsite construction industry needs and what laboratories are providing?
- What can be done to bridge this gap structurally, financially, and culturally?
- How can partnerships between laboratories and the offsite construction for housing industry develop into an innovation ecosystem for product R&D?

Develop supply chain standards to help foster a robust subassembly market.
Recent disruptions to the supply chain of construction materials have caused escalated prices and elongated schedules, resulting in increased housing costs and delivery times. Offsite construction has the potential to solve this challenge by developing supply chain standards—software applications (including *blockchain technology*), price management, stockpiling materials, and employing materials—in subassembly manufacturing (Perera et al., 2020). General contractors can reduce procurement management time and cost from this standardization; however, there is risk in relying on fewer subassembly suppliers, and there is a need for additional subassembly manufacturers to enter the offsite construction supply chain to codevelop and share knowledge of standards (Smith, 2010).

Related Research Questions

- Why have disruptions occurred in the material supply chain for construction generally?
- How are material supply-chain challenges impacting offsite construction for housing specifically?

- How can offsite construction foster more stability in the material supply chain for housing affordability through standards of software and products?
- What are the risks for project stakeholders in relying on significant means and methods with only a limited number of offsite manufactured subassembly supply chain partners?

Research international supply chain for offsite construction for housing in the United States

Supply chains are international. Although the scope of this report is concerned with U.S. offsite construction for housing, the offsite construction industry in the United states uses an international supply chain of materials. Furthermore, multifamily offsite construction projects in the planning stages in the United States will be procuring subassemblies from abroad. One example is the supply of 3D volumetric modules from Poland to the United States for hospitality projects and the related recent announcement of the U.S.-based vertically integrated housing company, Volumetric Building Companies, merger with Polcom, a commercial volumetric modular supplier in Poland. Research is needed to establish guidelines or standards for international subassembly supply chain in offsite construction and foster an international offsite construction trade economy.

Related Research Questions

- What are the material supply chain benefits and challenges that the U.S. offsite construction industry is facing when procuring from abroad?
- What are the subassembly procurement obstacles that the U.S. offsite construction-for-housing industry is trying to overcome?
- How can supply chain guidelines or standards help in addressing these barriers to subassembly procurement for offsite construction for housing?
- How can subassembly product standards aid in overcoming supply chain challenges in offsite construction?
- What software platform performance criteria does the international offsite construction supply chain need?
- How effective are existing software platforms and processes in international offsite construction subassembly procurement?

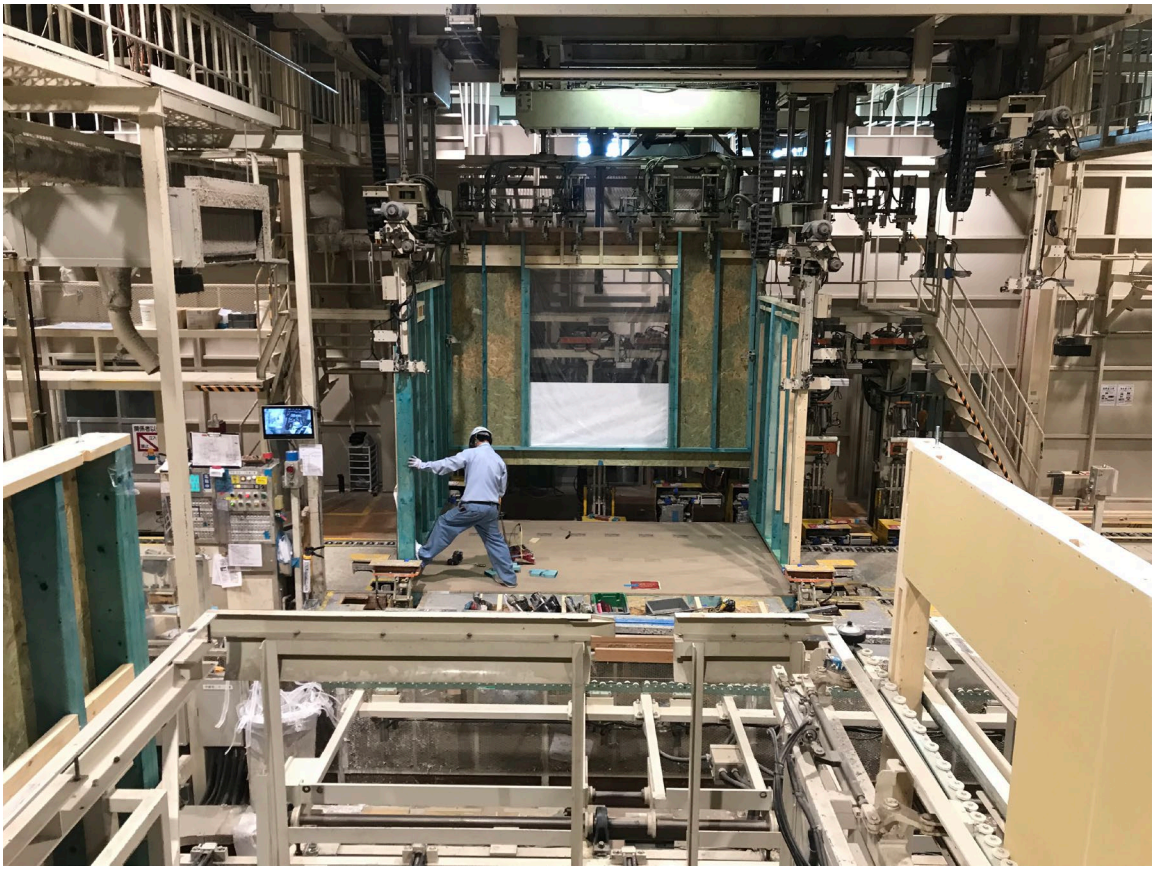
Assess supply chain limitations with emphasis on the quality of U.S. and Canadian nominal lumber.

There are several material products in the construction supply chain that are well established due to prescriptive codification in building regulations, conventions in labor practices, and materials on the jobsite. Offsite manufacturing and the employment of automation are revealing challenges to using conventional materials and labor practices in the factory setting. For instance, U.S. nominal lumber (2x4, 2x6, etc.) sourced domestically and from Canada is considered poor quality compared to European sawn wood. Mechanized and automated fabrication equipment from Germany and Sweden were designed to accommodate a higher-grade wood resource. As such, U.S. offsite manufacturers that are transitioning to automation are challenged with having to procure higher grade lumber or engineered wood products to take advantage of their capital investment (exhibit 15). Manufacturers who are not relying on automation are challenged to build a plumb structural frame to accommodate precise follow-on lining, insulation, finishes, and cladding.

Related Research Questions

- What supply chain materials and products are causing problems for offsite construction due to the lack of precision or inconsistent quality?
- What are the schedule, durability, and economic impacts of these materials on offsite construction delivery?
- How can standards for these materials increase quality and reliability of the offsite construction supply chain, and what standards should be developed as a result?
- What are the economic, workforce, and other impacts of having to procure higher-grade wood or an engineered wood supply for offsite manufacturing?
- What are additional potential solutions or products to overcome the poor quality of framing lumber supplied from the U.S. and Canada for offsite manufacturing?

Exhibit 15. 3D Volumetric Modular Robotic Orthogonal Assembly Jig at Sekisui Heim in Tokyo, Japan



Sekisui Heim uses a combination of engineered wood split studs on the end posts and king studs and sawn wood for infill framing to optimize cost and quality for 2D panel manufacturing that becomes 3D volumetric modules.
Source: MOD X

Develop dimensional design standards to create value.
Dimensional design standards have the potential to deliver great value in offsite construction for housing. Construction materials are standardized to two-, four-, and eight-foot lengths and widths (i.e., lumber and sheet products) and based on what one or two laborers can physically lift on a job site. Leveraging offsite manufacturing facilities, cranes, hoists, mechanization, and factory automation allows for potentially larger material dimensions and heavier material weight. Although material product dimensions are standardized, it is rare that design for housing follows a similar discipline in measurement regulation. Dimensional design standards are key to developing product platforms that can be configured across different buildings for improved quality and productivity (Habraken, 1972, 1974; Benson, 2008)

Related Research Questions

- What are established dimensional standards used by leading offsite construction practices in the United States and abroad?
- How have dimensional standards improved the design for manufacturing logistics, procurement processes, and project delivery for offsite construction?
- What additional dimensional design standards can be developed to benefit offsite construction for housing as an entire industry and not just for an individual company?
- What other benefits might be forthcoming by implementing an industry-wide dimensional standard for offsite construction in housing?
- How can dimensional standards for offsite construction for housing be shared openly in the industry?

Assess the value that product platforms in offsite construction provide to housing projects and stakeholders.
Product platforms, originally from the manufacturing and product design industry, are a collection of parts, components, and subassemblies that are common to different building configurations. The commonality is developed intentionally to achieve desired effects to create value. Product platforms employ a personalization strategy to design, thereby enabling economies of scale at the subassembly level to allow for increased variety at the building level (Muffatto and Roveda, 2002). The offsite construction for housing industry is beginning to develop product platforms in vertically integrated companies, as well as through collaborative partnerships, driven by the need to create value downstream for more affordable housing. However, the project-based and lifecycle value of product platforms in offsite construction for housing delivery is still unknown.

Related Research Questions

- What are existing examples of product platforms in the offsite construction housing industry in the United States and abroad?
- What project, lifecycle, and business benefits have been realized through product platforms for offsite construction for housing?
- How can precedents inform the development of an industry-wide product platform based on specific housing types?
- What partnerships and pilot projects might be used to test a housing type product platform for offsite construction?
- How can the lessons from the demonstrations be codified and shared openly?

Measure lifecycle sustainability of offsite versus onsite construction with a view towards more overall circular construction sectors.
Offsite construction proponents have claimed the environmental benefits of offsite construction for decades. Limited case studies have quantified the potential of offsite panelized and volumetric modular construction to reduce environmental lifecycle impact (Quale et al., 2012; Smith, Hamedani, and Griffin, 2018). Offsite construction provides a reduced construction schedule and is theoretically less disruptive to the environments in which it is employed. But additional research is required to determine not only characteristic values, but also demonstrative values for the social and environmental lifecycle improvements of offsite versus onsite construction based on several factors (e.g., site disruption, waste reduction, transportation reduction, etc.). Offsite construction methods present the potential of disassembly and reuse of building sections and materials, but the lifecycle assessment and the logistical and technical standards needed to achieve such potential have not been adequately researched.

Related Research Questions

- What is the demonstrative lifecycle impact of offsite versus onsite construction for housing?
- How can offsite manufactured products and practices improve the environmental impact of construction?
- What examples of offsite construction disassembly and reuse for circularity exist internationally, and what impact did these case studies have on the environment?
- How can these lessons and practices be transferred to the U.S. offsite construction for housing sector?
- What is an offsite construction circularity program that can be tested through pilot demonstration projects?

Offsite construction provides a repeatable, cost-effective mechanism to meet our nation's growing housing demand. Setting up a factory for offsite construction is a unique opportunity to make a huge impact on our building stock for the next 100 years plus. This is the time to better understand how this type of construction can impact our global carbon footprint and implement whatever is needed to lower it.

- Cheryn Metzger, Pacific Northwest National Laboratory

Evaluate building performance challenges and opportunities.
As the offsite construction industry continues to mature in the United States, involved stakeholders are experiencing several technical challenges and opportunities. The PTC members and workshop participants listed the following as priorities to be addressed through additional research, including:

- Structural load path and site structural connections for enclosed construction.
- Hybrid offsite construction structural systems compatibility and connections onsite.
- Factory-installed insulation settling during transportation and handling.
- Factory-installed air tightness measures compromised during transport.
- Gypsum wall board factory-installation bottlenecks and damage in transport and handling.
- Water mitigation strategies and practices during transport and site setting.

- Fire and sound attenuation performance characterization of established offsite construction subassemblies with ICC-ES Reports (2D enclosed panels and 3D volumetric modules) and final installed performance assessment.
- Shallow frost-proof foundation systems for HUD Code housing cost and structural performance.
- Temporary foundation systems for temporary IBC Code housing on land bank sites.

These building performance challenges and potential solutions can be researched conceptually and simulated digitally. However, participants indicated that at a certain point in the research development, the investigations will need to engage in live pilot demonstration projects with project stakeholders and researchers for the greatest value and offsite construction improvement.

Related Research Questions

- How can these listed building performance challenges be verified and additional barriers identified?
- How do these challenges negatively impact project delivery schedules, cost, and performance?
- What are product and process solutions to overcoming the most pressing building performance challenges for offsite construction for housing?
- What solutions are intellectually protectable, which are generalizable, and how can research be framed for open access?

3.3 Research Topic 3: Capital, Finance, and Insurance

Finance will follow confidence in modular, and confidence in modular does not yet exist in AHJs. The industry is fractured, and so stabilization for the industry is key. What can bring stability? Risk mitigation to all parties is key to stabilization.

- Laurie Robert, Modular Building Specialist

A common thread across most of the research topics is that many of the obstacles to offsite construction growth in the involved stakeholders originate from traditional capital, finance, and insurance markets that are designed to support conventional construction methods. The financing of HUD Code homes, for example, has been a persistent challenge that has limited the viability of this longstanding offsite construction program. PTC members and workshop participants overwhelmingly agreed that securing capital for offsite construction manufacturing facilities and financing for individual projects is a major obstacle, on par with the current regulatory framework and standards challenges. A lack of education, knowledge, and awareness within the developer, lending, and insurer communities related to offsite construction is deemed a major root cause of this persistent obstacle.

Offsite manufacturing is a capital-intensive activity. Factories starting up or pivoting to a different type of offsite manufacturing incur debt or equity to secure capital. This is a challenge due to the time lapse between getting a factory up and running and generating a return on investment (ROI). Participants indicated that there is simply not enough capacity in the offsite

manufacturing sector for housing in the United States. Factories are not supplying enough product at scale, and there are too few factories that are geographically distributed to meet existing and potential housing demand. This challenge is further compounded by project-specific financing that often encounters delays from lenders and insurers, which subsequently cause production delays that are difficult to manage for offsite manufacturers. Additionally, when project-specific financing is eventually secured, manufacturers cannot easily scale-up production due to a lack of long-term financing for increased mechanization, automation, and R&D. The timeline, schedule, and cycles of housing development and construction with the associated finance required, and the need for offsite manufacturers to keep the factory line flowing with their related capital needs, are fundamentally not aligned.

During the PTC sessions and workshops, several publicly funded offsite construction programs, including the HUD Operation Breakthrough and HUD Code housing programs, were cited as illustrations of providing the offsite construction industry a desperately needed large-scale market catalyst in the form of capital investment. The HUD Code housing market in the United States is the only segment of the offsite construction industry with a small number of large, consolidated companies, most of whom have been operating since the mid-1970s when these public programs were first introduced. PTC members and workshop participants also provided several examples of effective programs implemented in Europe and Asia that provide similar market catalysts to local offsite construction industries. Technology companies in the United States and international investment groups were also discussed as indicating increasing interest in investing in offsite construction. Some degree of public investment was generally seen as (1) a way of overcoming the capital-intensive obstacles encountered by any manufacturing industry, particularly those historically affected by variable economic cycles impacting demand, and (2) an effective method of overcoming ubiquitous industry stigma associated with an “emerging” form of construction, thereby establishing critical market confidence that positively impacts the entire ecosystem, including capital, finance, and insurance institutions.

Fundamentally, offsite manufacturing start-up and operational capital and project-based finance and insurance have not been easily obtained, primarily because offsite construction is still considered a risky proposition by investors, lenders, and insurers. Participants identified several research subtopics that can help to overcome the offsite construction risk profile challenge, provide greater market confidence, and identify how public funding projects can support the evolution of offsite construction for housing.

Capital, Finance, and Insurance Research Subtopics

Study the developer and lending risk associated with offsite construction in various segments of the housing market.

Any change in the delivery model for construction presents opportunities and challenges, perceived and real. Offsite construction promises to control cost, reduce schedule, and mitigate worker safety liability; however, it continues to be perceived as a higher risk for developers and lending institutions than conventional construction. Additional research is required to determine the actual benefits and risks realized in practice and how offsite construction needs to effectively address and attenuate the associated risks. Industry best practices and 'how-to' guides can also generate developer and lender confidence in offsite construction for housing solutions.

Related Research Questions

- What is the quantified project finance risk profile of offsite construction versus traditional construction by housing type and market?
- What are the qualitative determinants that lending institutions are using to assess the risk of offsite construction?
- What data and education are needed for the finance industry to gain confidence and determine that offsite construction for housing has no added risk or lower risk than traditional construction?

Identify financial methods and mechanisms to provide better upfront project finance and insurance bonding for offsite construction.

Construction finance and insurance are generally based on traditional onsite delivery and draw on conventional construction loans and bonded professionals. Developers are reporting challenges associated with upfront deposits required by offsite manufacturers to secure a factory production line for their respective housing projects. In addition, developers encounter incremental costs of design fees for investing increased time in greater levels of development in concert with offsite construction manufacturers and GCs in integrated design assistance. The scope and related insurance bonding between factory (manufacturer) and jobsite (GC) are evolving and inherently risky. Thus, there exists a need for developers and lenders to secure upfront gap financing for offsite construction projects and methods of defining scope delineations more clearly.

Related Research Questions

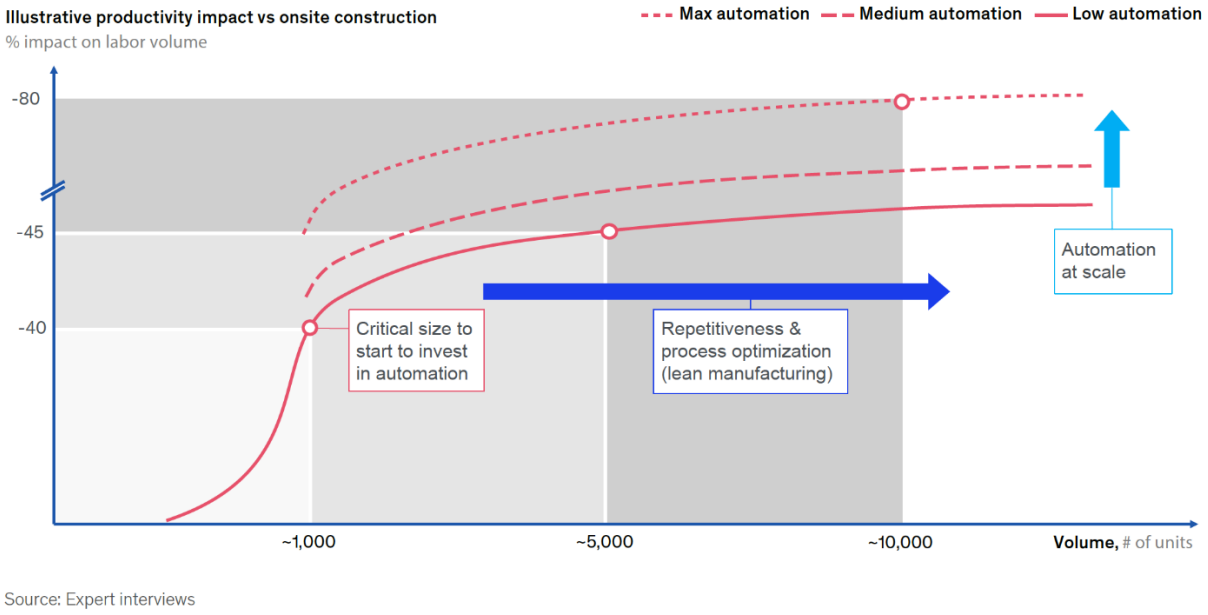
- What is the financial flow that disconnects traditional construction lending and offsite manufacturing from construction finance needs?
- What are the insurance and bonding challenges associated with offsite construction?
- How can offsite manufacturers develop more confidence for lenders in upfront finance and more predictable and secure manufacturing line flow?
- How can offsite manufacturers foster confidence for insurers on offsite construction projects?
- What can developers and GCs do to address project finance and insurance obstacles on the demand side of finance?
- What are alternative finance and insurance vehicles and programs for offsite construction for housing projects?

Assess the opportunities and challenges of debt versus equity capital for start-up and R&D manufacturer funding in offsite construction to increase capacity and capability.
Offsite manufacturers for IRC and IBC housing are emerging using different business models in the United States. (Lessing and Brege, 2018; Smith and Rupnik, 2020). A common approach is HUD Code manufacturers transitioning to permanent modular manufacturing for multifamily commercial projects to diversify their portfolios and pivot during housing market shifts. Open panel manufacturers, likewise, may transition to enclosed-panel manufacturing as an attempt to create additional value through added insulation and lining enhancements. Furthermore, some 2D and 3D enclosed subassembly manufacturers are providing additional design and engineering services, as well as onsite assembly and warranty services. Similarly, material manufacturers and suppliers, as well as architects and engineers, are migrating downstream to provide value-added subassemblies. In the past decade, some GCs have moved upstream to manufacture subassemblies as well. In addition to supply chain expansion and mergers, new market entrants and start-up subassembly manufacturers, as well as *vertically integrated* housing companies, are advertising offsite manufacturing and construction businesses for housing (See section 3.6 Business Models and Economic Performance). Considerable capital is required to make offsite manufacturing operational, whether for existing supply chain partners to pivot in products and services or for completely new entrants to the offsite construction market. This required capital can originate by way of debt or equity, or a combination of both. Capital investment is needed if offsite manufacturing is going to expand in capacity and capability to meet the current and future demand for housing in the United States.

Related Research Questions

- What are the opportunities and challenges of debt-versus-equity capital models for funding offsite manufacturing startup and operations?
- What is the return on investment (ROI) of offsite manufacturing by subassembly type, housing market served, and volume of supply? (exhibit 16)
- What are the challenges for existing supply chain partners migrating upstream or downstream in offsite manufacturing?
- How are design and engineering and site-assembly services monetized in offsite construction?
- How can offsite manufacturers ensure a more consistent factory production flow to maximize overhead and attenuate production uncertainties?

Exhibit 16. Offsite manufacturers' critical size to invest in automation is estimated at 1,000 subassembly units (panel or 3D Volume) per annum.



Source: McKinsey; Bertram et al., 2019

Identify obstacles to domestic and international investment in offsite construction to further stimulate industry growth.

Several domestic and international investors have established new entities or facilitated investments in existing offsite manufacturers in recent years. Unfortunately, a number of these ventures have failed and consequently generated negative press coverage (Davis, 2021). The rate of failure of offsite manufacturers is disproportionate with the failure rate of other construction endeavors (Smith and Rice, 2015b). The hypothesis has been that disruptive approaches to venture-capital offsite manufacturing are not as successful as an incremental sustained growth model (Smith and Rupnik, 2020). A primary reason for the failures is that the people, processes, and products were not adequately researched to guide current and future offsite manufacturers and respective investors (Goulding and Arif, 2013). Research is needed to determine: (1) why offsite manufacturers fail and (2) what information is needed to boost investor confidence in offsite manufacturing business.

Related Research Questions

- What case studies and macro-market-level data can be analyzed to address the question of why offsite manufacturers for housing fail?
- What information do international and domestic investors need to determine the risk profile and ROI potential of offsite manufacturing and construction for housing?
- How can the offsite construction industry answer the needs of investors for offsite manufacturing operations capital?

Analyze various offsite construction production systems regarding capital, finance, and insurance.

Not all offsite construction systems are equal with respect to capital, finance, and insurance requirements. Although some of the factors for risk assessment and ROI for lenders, insurers, investors, developers, and other stakeholders are universal, many are specific to the market and the technical subassembly being manufactured. Subassemblies have a sliding scale of enhancement and level of completion. Furthermore, they are designed and manufactured specifically to a product platform, business platform, and market need, and therefore they may vary widely. However, to address the need for the industry to evolve and move forward, the most common offsite subassemblies for housing can be analyzed, including, kit of parts, 2D open panel, 2D enclosed panel, 3D volumetric modular, and HUD Code. Furthermore, the level of digitalization, mechanization, and automation varies by subassembly type and the housing market served (single-family or multifamily, market rate, or affordable housing). Research is needed to determine the capital, finance, and insurance risk profiles and potentials specific to offsite subassembly type, level of automation, and housing market to be served.

Related Research Questions

- What are debt and equity investment capital needs specific to the most common offsite subassembly types (i.e., kit of parts, 2D open panel, 2D enclosed panel, 3D volumetric modular, and HUD Code)?
- What are the finance-lending parameters that are unique by offsite subassembly type?
- What are the insurance and bonding requirements based on offsite subassembly type?
- What are the levels of digitalization, mechanization, and automation possible for the various offsite subassembly types, and how does this impact capital, finance, and insurance?
- How are subassembly types and levels of automation related to the housing market to be served (i.e., single-family, multifamily, market rate, or affordable housing)?

Investigate how more developed international offsite construction industries have managed capital, finance, and insurance.

Japan, Sweden, and the United Kingdom (Scotland) have been developing single-family and multifamily offsite construction for housing (panelized and volumetric) for 30 to 40 years and penetrating up to 30 to 70 percent of the total housing development new buildings (Bertram et al., 2020; Deakin et al., 2020; Hairstans and Sanna, 2017; Smith et al., 2013). These mature offsite construction markets can provide valuable knowledge and transferrable lessons to the U.S. context regarding how finance, investment, and insurance have interacted with and nurtured growth of the offsite construction industry over time.

Related Research Questions

- What lessons can international offsite construction industries provide regarding startup operational capital for offsite manufacturers in housing?
- How have international markets for offsite housing construction overcome finance disconnects between the needs of manufacturing funding and construction lending practices?
- How have international precedents handled insurance and bonding risk-mitigation requirements?
- How have international offsite manufacturers ensured a more consistent factory production flow?

3.4 Research Topic 4: Project Delivery and Contracts

The move from single, one-off projects into a stream of buildings being produced by a platform really speaks to the urgent need to diversify production strategies in construction. There is a place for unique and bespoke buildings. There is also a place for standardized mass customization. Thus, we also need to develop our models for project delivery. Why couldn't a manufacturing platform be preapproved by an accredited body to expedite approvals and inspections?

- Helena Lidelow, Lindbäcks Bygg AG

Current models of project delivery in the architecture, engineering, and construction (AEC) industry are often considered an impediment to increased construction productivity, whereas new models like design-build or integrated project delivery continue to gain traction (Carraher and Smith, 2017). Conventional project delivery approaches and the contracts that frame them generally delay decisions about the means and methods of construction until late in the process, with project documentation changing frequently throughout. Offsite construction generally requires earlier decisions in the overall project schedule and more coordination between the project team and the manufacturer versus conventional construction (Smith, 2010). When serving the single-family market, offsite manufacturers have managed to work within the conventional project delivery and contract system, but participants acknowledge that growth in demand for multifamily housing has proven this misalignment to be highly detrimental to project outcomes.

Vertical integration has allowed a small number of offsite construction companies to partially overcome some of these challenges by controlling a greater portion of the entire process and modifying the project delivery structure. However, the majority of U.S. offsite construction capacity is still built around suppliers of panelized or volumetric modular solutions that attempt to work within the conventional project delivery framework and supply a commodity subassembly. In more developed international offsite construction industries, several strategies have been effectively deployed to overcome the misalignment that exists in the United States, with offsite construction companies leading the way to an AEC-wide transformation of project delivery standards and supporting contracts.

The NIBS OSCC, PTC members, and workshop participants all identified the misalignment between conventional project delivery and offsite construction as a major obstacle for offsite construction implementation. Integral to modifying project delivery norms, education of architects, engineers, and developers with respect to offsite construction was widely discussed as an effective first step in the process. Participants also identified close links between the regulatory framework, finance, insurance, project delivery, and contracts, with meaningful change only possible if all of them were considered an interconnected set of issues. Some experts argued that regulation and finance challenges would need to be resolved before establishing substantive project delivery changes. The current project delivery system of design-bid-build was discussed as creating oppositional relationships between project teams.

In the short term, revision of contracts by the key trade associations would assist alignment of the project delivery process with offsite construction. A key step in this process has been the collaborative work of the MBI and ICC on a set of American National Standards Institute standards for offsite construction, with one, ICC/MBI 1200, focused on the design, fabrication, construction, and assembly of IRC and IBC offsite construction projects. This is not a contract; rather, it provides a process guide for project stakeholders. Further, the Associated General Contractors (AGC) has developed the Consensus Document 753 Standard Prefabricated Construction Agreement Between Constructor and Prefabricator (2020). This is a contract form between the offsite manufacturer and site that the AGC intended to address contractual and procedural scopes and relationships between the factory and site. Similar work needs to be prioritized between the AIA and other relevant trade associations for the development of additional guidelines and standards for offsite construction stakeholders. These changes would support the offsite construction industry at-large, especially the offsite manufacturers who prefer to work solely as suppliers of offsite manufactured components.

In the long-term, some PTC members and workshop participants discussed a shift required to a manufacturing-like project delivery system whereby offsite construction companies would move away from one-off project-based delivery to product platforms. Product platforms are "a collection of modules or parts that are common to a number of products" that are "developed intentionally to achieve desired effects to create value" (Harland, Uddin, and Laudien, 2020). Instead of submitting a set of complete documents to an offsite construction company or "designing for manufacture and assembly," a client is presented with a set of predesigned parameters within which to work (Jensen, Lidelow, and Olofsson, 2015). These parameters vary depending on a particular market sector, and the approach is still quite rare in the U.S. AEC sector. However, in more developed offsite construction countries like Japan and Sweden, the approach is well established, just as it is in nearly every manufacturing industry globally.

Moving to a product platform approach requires different levels of design documentation and connection to manufacturing. Also, participants noted that there continues to be a disconnect between design software and manufacturing software that follows the conventional practice, which contractually and culturally separates design from the means and methods of construction. Digital workflows are quite different when design, manufacturing, and construction are considered a continuous process, with the roles and responsibilities of the parties becoming much more enmeshed. Participants noted the recent employment of *digital twins* in offsite construction, by which a virtual representation of the building and its systems spans the project delivery timeline and is updated in real-time by stakeholders. Also, participants indicated that there are no established guidelines for project documentation, *level of detail (LOD)* in *building information modeling* (BIM), and digital twin workflow for offsite construction for housing in the industry.

Project Delivery and Contracts Research Subtopics

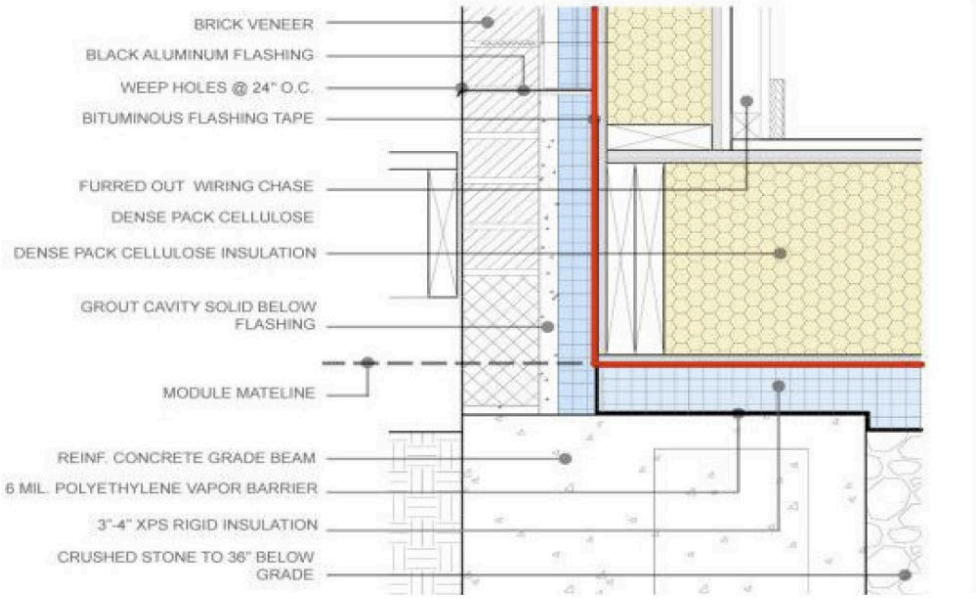
Assess the appropriate level of project documentation for offsite construction through the various stages of project delivery.
Project documentation, drawings, and specifications are conventions utilized in design to communicate the program, scope, and intention for construction delivery. Offsite construction requires considerably more information from the design team early in the project; it needs a

greater LOD for means and methods information that is not usually required for traditional delivery. As the industry has migrated to new processes for project documentation through the employment of BIM, there is no clear understanding of the appropriate LOD, digital twin guidelines, and best practices for offsite construction as a project moves through phases of design, manufacture, and construction development. Furthermore, there is no project delivery guide or standard that outlines the responsible parties for documenting (design-to-manufacture-to-construction) and completing the scope (factory-to-site).

Related Research Questions

- What are the appropriate levels of detail required in offsite construction for housing documentation at the stages of progression in project delivery?
- How should design documentation provide the proper amount of information for offsite manufacturing and onsite assembly?
- What are best-practice conventions for delineating factory and site scopes of work in project documentation? (see exhibit 17)
- Who should develop, maintain, and revise project documentation during the project delivery process and lifecycle phases for offsite construction?
- How does project documentation change when considering different subassemblies and housing types in offsite construction?

Exhibit 17. Light Wood Framed 3D Volumetric Module Set On-Site-Built Foundation with Site-Applied Exterior Insulation and Brick Veneer for a Row Housing Project



Note: The red line delineates the respective offsite versus onsite scopes.
Source: Onion Flats

Evaluate and revise conventional contracts for offsite construction project delivery to better align compensation and scope of work.

Construction contracts are not currently standardized. However, most private projects utilize AIA Contracts or AGC ConsensusDocs contract structures. These contracts were developed based on traditional site-built construction. AIA contracts tend to favor architects, and AGC ConsensusDocs tend to favor builders. Neither are particularly well-suited for the nuances of offsite construction delivery, according to project stakeholders. There is a need for additional research of traditional contracts, their limitations, and how effective the various models of design-bid-build, design-build, construction manager-at-risk (CMAR), and Integrated Project Delivery are at successfully facilitating offsite construction delivery and how these contracts can be amended to support offsite construction. In addition, governments may have their own contracts and procedures for project delivery outside of AIA and AGC contracts. PTC and workshop participants indicated that some of these contracts have language that is unsupportive of offsite construction use or are silent on the question of offsite construction for government facilities. Research is needed to investigate government contracts at the local, regional, and federal levels and to identify opportunities for being inclusive of offsite construction for housing.

Related Research Questions

- What are the challenges with using conventional AIA and AGC ConsensusDocs for offsite construction delivery?
- What language needs to be revised in these contracts to ensure they are not limiting offsite construction for housing?
- How are government contracts limiting the use of offsite construction for housing?
- How can government contracts be revised to be inclusive of offsite construction for housing?
- Are these contract limitations based on housing type and subassemblies used in offsite construction?
- How are limitations different for conventional and government contracts for various housing types and subassemblies used in offsite construction?

Evaluate new project delivery and contract standards to support increased innovation and competitiveness in the offsite construction sector.

To overcome the challenges associated with traditional AIA and AGC contracts, the ICC, in a consensus process, has developed a guide for project delivery (ICC/MBI, 1200). Although this guide does not fundamentally change contracts, the tools are intended to provide project stakeholders with a process to attain success in project delivery. Additional research is required to properly assess the project-delivery guide. Furthermore, MBI partnered with the AGC to collaboratively develop the ConsensusDocs 753 for offsite construction as a contract structure between the offsite manufacturer and site GC. Since this is a newly established contract altogether, additional research is needed to properly test and assess the contract, with the key lessons compiled and disseminated for further refinement and stakeholder education. International offsite construction markets can also be a source of effective offsite construction contract precedents and project delivery guides and standards.

Related Research Questions

- What are the project-delivery benefits and challenges of using ICC/MBI 1200 through pilot testing?

- How can this standard be improved, or additional guides and standards be developed, to foster project-delivery success in offsite construction?
- How effective is AGC ConsensusDocs 753 as a contract structure for offsite construction success?
- What can be improved in the AGC ConsensusDocs 753 for project delivery?
- How do different housing types and subassemblies affect the use and success of ICC/MBI 1200 and AGC ConsensusDocs 753?

Develop and assess single-source subcontracts in construction and the role of offsite construction in delivering such contracts.

Generally, construction is moving toward more consolidated single-source subcontracts that follow building-system lines, including site preparation, structure, envelope, interior fit-out, and mechanical/electrical/plumbing activities. This approach reduces the number of contact and contract points for the GC and owner, and it conceptually reduces project timelines. This is important when there is a dearth of an available workforce for construction broadly. Offsite construction is gradually migrating toward more consolidated and integrated subassemblies (larger elements) as well. Therefore, research is required to properly assess the relationship between single-source subcontract models and offsite construction. Additional research is also required to assess the impact of single-source subcontracts on total project value, fostering new, as opposed to established, players and overall innovation.

Related Research Questions

- What is the qualitative and quantitative total project value of single-source subcontracts in construction generally?
- How can the current offsite construction supply chain provide single-source system solutions for structure, envelope, interior fit-out, and MEP functions?
- What needs to change in the manufacturing of subassemblies and procurement for offsite construction to meet the needs of single-source contracts?
- How do the different housing types and offsite manufactured subassemblies affect the use of single-source contracts?

Investigate contracts and project delivery standards outside of the U.S. offsite construction sector.

Internationally, Japan, Sweden, and Australia have all developed an approach to project-delivery standards and contracts to meet the growing demand for offsite construction for housing. Also, there are several production industries that provide models which may be applicable to offsite construction in the United States. Lessons from automobile manufacturing provide important examples for improving project delivery (Gann, 1996; Aitchison, 2017), and contracting in the film industry partially mirrors the multiple contract nature of construction (Ebbers and Wijnberg, 2009). These international offsite construction contracts and project-delivery standards, as well as lessons from other industries in the United States and abroad, can provide precedents to improve offsite construction for housing delivery in the United States.

Related Research Questions

- What international offsite construction contracts and project delivery standards for housing can inform the U.S. context?

- What contracts and project delivery methods can be adopted from other industries and tested in the offsite construction-for-housing sector?

3.5 Research Topic 5: Labor and Workforce Training and Management

Off-site construction presents a significant opportunity to broaden the construction workforce to women and to less skilled or hard to place workers. It can confer significant benefits to families and the environment, such as less commuting and job stability. Yet there is much learning needed to understand best practices for recruiting, retention, and training.

- Carol Galante, UC Berkeley

The growth of offsite construction is closely tied to overcoming a variety of barriers in labor and workforce training and management. Historically, negative perceptions have existed with respect to offsite construction by existing labor institutions, and especially organized labor, due to an underlying belief that the approach will result in job elimination (Haas et al., 2000). More recently, a general decrease in construction labor availability has led to an increasing interest in offsite construction among governments, and the construction industry globally, as a method of increasing productivity within the context of a declining labor pool. More developed international offsite construction industries have demonstrated that the approach can provide higher paying and more stable employment that is similar to manufacturing jobs in other industries (exhibit 18). In both the offsite and onsite construction context, industrialized construction allows for a more diverse group of individuals to participate in the construction process. The current division of responsibility between offsite manufacturing and onsite assembly and finishing of subassemblies also creates a unique set of challenges to the U.S. offsite construction industry with respect to workforce training and management.

Exhibit 18. In mature offsite construction industries overseas, the approach has been to increase the diversity and desirability of construction jobs among organized labor and the public.

Source: Lindbäcks Bygg AB

PTC members and workshop participants discussed the need for a concentrated focus on education and training across the industry. In addition to educating the workforce inside a factory environment, education and training of the entire AEC industry, with respect to offsite construction, remains critical for transforming offsite construction into a technology industry. Relationships with unionized labor and prevailing wages (Davis Bacon Wages) were also identified as persistent challenges to offsite construction. Positive examples of better collaboration between offsite manufacturers and organized laborers were discussed, such as the work of Factory_OS and the Northern California Carpenters Union (NCCU).

The offsite manufacturers, and more specifically 3D volumetric manufacturers, are facing an aging workforce, especially among senior management. In many cases, the next generation of privately owned volumetric modular manufacturing companies in the United States are not willing to run the businesses. Promoting new management, especially as volumetric modular manufacturers provide training and upscale their processes to meet growing demand in multifamily housing, will be key for success in the future of offsite construction for housing in the United States. Persistent challenges to attracting, managing, and retaining a vibrant and engaged workforce in offsite construction operations and in factories are also attributed to an "incomplete evolution" of the industry from conventional construction (building under a roof) to a "tech industry" (modern manufacturing). PTC members and workshop participants identified the absence of a "manufacturing mindset," with regards to labor, and a lack of "standardized processes," including lean management principles and other forms of modern management typically implemented in other manufacturing industries.

Education and training for the onsite portion of offsite construction were also identified as particulars concerns. Although factory employees benefit from increased job security and training more than typical construction laborers, site crews do not. More vertically integrated companies have inherently solved this problem by either utilizing the same labor for offsite and onsite construction work or by offering specialized training for onsite crews. For most of the industry, there remains a significant division of scope-of-work that in turn leads to a general lack of knowledge about offsite construction for onsite assembly, with only a few exceptions cited as construction companies that specialize in the onsite portion of offsite construction.

Labor and Workforce Training and Management Research Subtopics

Assess the benefit of life-safety and reduced-risk profile and the associated cost of offsite versus onsite construction.

Offsite construction seems to be a solution to life-safety concerns associated with traditional onsite construction. Manufacturing is historically safer for a workforce than construction (Ahn et al., 2020). Workers coming to the enclosed, conditioned environment of the factory to perform work each day that is predictable, ergonomically responsive, and in some cases repetitive, improves worker health and wellbeing. Life-safety has a social and economic cost associated with this underlying risk. Additional research is required to determine the workforce and labor life-safety impacts of offsite versus site-built construction delivery. Also, this research needs to determine the social and economic cost-benefits and challenges associated with offsite construction versus conventional delivery.

Related Research Questions

- What are the quantified life-safety improvements realized in offsite construction when compared with conventional construction?
- How are life-safety benefits factored into insurance risk assessment and associated economic costs?
- What are the social impacts of offsite construction when compared with conventional construction (i.e., health, wellness, satisfaction, pay, career progress, skills, etc.)?

Identify current barriers in offsite manufacturing to successfully recruit, retain, and train a workforce.

The availability of a workforce in construction continues to be a challenge across the industry. The lack of labor has led to increases in housing design and construction costs (Nguyen et al., 2020). Offsite construction has been identified as a strategy to address the declining labor force due to the more efficient and productive use of labor (Smith, 2016). Regardless, offsite construction is challenged with attracting workers, collaborating with unions to manage labor requirements, and positioning construction as a manufacturing and technology industry. Within the offsite construction industry, laborers migrate to different companies in their regions through labor wars. Like onsite construction, offsite construction experiences variable labor cycles. Within a manufacturing environment, balancing fluctuation in project schedules with the need for consistent production line throughput is particularly challenging for workforce development, training, and realizing the benefits of offsite construction production productivity. Additional research is required to develop effective plans and policies to address these ongoing challenges

and overcome the barriers to recruitment and retention of a workforce in offsite manufacturing operations.

Related Research Questions

- What are the driving factors that lead to workforce turnover in offsite construction?
- What are methods to attract and retain workers in the offsite construction industry?
- How can factories manage workforce turnover with manufacturing schedules and inconsistent factory volume throughput?
- What are ways in which offsite manufacturers can work with and through organized labor to the benefit of both the workforce and factories?

Develop methods to diversify the workforce to attract and retain labor outside of the offsite construction industry more broadly.
Currently, only 9 percent of the construction labor force is female. Conversely, the manufacturing sector generally employs a 30-percent female workforce. Offsite manufacturing has the potential to attract a workforce that is not currently moving into construction generally. Additional research is required to determine how to effectively recruit female and minority demographic populations to offsite manufacturing employment to increase diversity and the number of laborers in the workforce. Key lessons can be compiled and disseminated from international offsite construction case studies and from other manufacturing industries.

Related Research Questions

- How can offsite manufacturers recruit workforce populations outside of the traditional construction demographic to include female and minority populations?
- What are the characteristics of a company that these workforce demographic groups are searching for, and how can offsite manufacturers evolve to meet these interests?
- How can the offsite construction sector mature into a technology-enabled industry to both increase performance and recruit and retain a new workforce?
- What marketing strategies can the offsite construction industry use to attract talent?
- What is a program to partner offsite manufacturers with high schools, secondary educational institutions, and apprenticeship programs to provide a trained workforce and labor pipeline?
- What have more evolved offsite construction industries internationally done to recruit and train workers?

Assess the relationship between organized labor and offsite construction.
Historically, there have been challenges with unions and organized labor regarding offsite manufacturing in locations around the United States, most recently in San Francisco (Dineen, 2020). Workers claim that offsite construction lowers standards and reduces wages. Given the labor crisis in construction generally, the resistance to offsite construction from unions has declined in the past decade. There is evidence of factories working with trade unions to address their concerns, but more research needs to be done to determine how to manage union relations through offsite manufacturing and to manage potential gaps in prevailing wages and benefits offered to construction site labor versus factory manufacturing labor. Furthermore, the health and wellbeing benefits of manufacturing versus the life-safety concerns of conventional site construction have not been adequately considered.

Related Research Questions

- What are the primary concerns of labor unions toward offsite construction by region and trade type?
- How can these concerns be addressed by offsite manufacturers, and what case studies demonstrate success in working with organized labor?
- What are the quantified benefits of offsite manufacturing versus onsite construction work that are not being considered?

Identify successful models for management recruitment and training for offsite manufacturers.

The aging workforce in offsite manufacturing, and an increasing number of senior management personnel that are scheduled to retire, were identified as particular concerns. An ongoing threat associated with management departure is the loss of valuable industry knowledge, network relationships, and mentoring capacity. The industry has historically struggled to promote from within and recruit from outside the offsite construction industry for its companies. The offsite construction industry, and more specifically volumetric modular companies, is culling and consolidating, vertically and horizontally integrating, and establishing joint ventures, which deems small-family modular businesses less viable and less attractive to future managers. Moreover, the nature of offsite manufacturing is rapidly evolving and is inherently riskier, more complex, larger in scale, and more involved in project delivery. Additional research is required to identify models for recruiting and training offsite construction management for this new business landscape in offsite manufacturing.

Related Research Questions

- How significant is the aging management workforce turnover in offsite manufacturing companies in the United States?
- What will be the benefits, challenges, impacts, and opportunities of this management turnover in the offsite construction-for-housing industry?
- What are methods to attract and retain senior management in offsite manufacturing companies?
- What are the characteristics, skills, and knowledge that the offsite manufacturing industry needs to search for in new senior management for a changing offsite construction market?

Investigate the levels and types of skills needed for the offsite construction workforce across the supply chain.

Offsite construction is different than conventional construction. It requires some of the same skills as traditional delivery, but it also needs unique skills and knowledge. These needs also vary depending on the supply-chain operations being performed. The stages of offsite construction delivery, including development, design, engineering, manufacture, assembly, commissioning, and maintenance, may require fewer, more, or different skills than conventional construction, depending on the housing type and subassemblies used. Therefore, research is needed to determine what knowledge gaps exist in project delivery and the supply chain for offsite construction. Furthermore, research is needed to develop a program to educate the existing and future workforce to improve skills.

Related Research Questions

- How are skills and knowledge different for offsite construction when compared with conventional construction, considering the different project delivery stages and different operations being performed in the supply chain?
- How are skills and knowledge requirements different in offsite construction, depending on housing type and subassemblies being used?
- What is a program for education and certification in the United States that can be applied in the offsite construction industry workforce training to address the unique skills needed for project delivery?
- How can this program be comprehensive but also flexible and customized to unique housing types, subassembly types, and company cultures?
- How can a comprehensive education program allow for future updates as the offsite construction-for-housing industry continues to mature and evolve?

Assess the benefit of trained management and labor involved in both offsite and onsite construction scopes-of-work.
The party that performs onsite assembly of offsite manufactured subassemblies varies widely. This party can be the subassembly manufacturer, GC, or a third-party subcontracted set crew. Offsite construction stakeholders are considering certification programs for setting subassemblies onsite to reduce the risk of handling. Additional research is required to assess the impacts and project performance outcomes with each of these parties performing onsite assembly work. Research is needed to develop alternatives or future practices for the parties that are currently managing onsite assembly.

Related Research Questions

- What are qualitative opportunities, challenges, and trade-offs associated with each of the following parties performing onsite assembly work in offsite construction: subassembly manufacturer, GC, and third-party set crew?
- What are the quantitative costs, schedules, and worker safety implications of the different parties performing onsite assembly?
- What site-assembly party knowledge can be learned from international offsite construction contexts?

Research the labor and workforce knowledge gaps in site assembly for offsite construction projects and develop educational and training programs.
Industry stakeholders continue to identify onsite assembly challenges as a primary barrier to realizing the total project value of offsite construction. Offsite construction may rely on manufacturers to serve as GCs and site crews and independent GCs to facilitate site scope, or they may employ an offsite construction third-party set crew to assemble the project. Given the variety of parties that may be responsible for completing site-based scope of projects, additional research is required to compile, analyze, and disseminate relevant site-based knowledge and best practices so that more offsite construction projects are successful. As identified by the PTC and Workshop participants, persistent challenges and pertinent site-based topics to be addressed include, but are not limited to, the following:

- Foundation preparation for offsite manufactured subassemblies, including tolerances, quality control, specifications, etc.
- Water mitigation strategies and practices during transport and site setting.
- Subassembly transportation best practices and minimizing damage.
- Optimal site staging and offsite construction subassembly preparation for setting.
- Optimal craning procedures to handle subassembly size/weight and to reduce time and cost.
- Training site crews on scope-of-work definition guidelines between factory and site.
- Closing-up exterior envelopes and completing interior finishes of offsite construction projects.

Related Research Questions

- How can these listed onsite assembly challenges be verified for their frequency, significance, and project-performance impacts (cost and schedule)?
- How can best practices be codified and disseminated for offsite construction site assembly training? (exhibit 19)
- What is an educational program for training site-assembly GCs and CMs to overcome challenges associated with transport, staging, setting tolerances, water management, scope definitions and coordination, MEP connections, exterior envelope, and interior finishing?

Exhibit 19. Four 3D Volumetric Boxes Joining at a Structural Connection for a Multifamily Development

Notes: The quality of the lumber causes tolerance concerns during offsite construction assembly on the jobsite. The quality of site installed fireproofing, sound attenuation, and finishing onsite is a challenge with offsite construction.
Source: MOD X

3.6 Research Topic 6: Business Models and Economic Performance

Don't take the land, produce massings that generate maximum gross square footage, and slice them up into apartment units to maximize revenue. Optimize the product and then aggregate and configure it to different projects sites. While you may miss a few units on one site, you can deliver an entire additional project with the time savings and provide a much improved, higher quality and livable housing product for the market at a significantly lower cost.

Justin Stewart, Synergy Modular / Synergy Inc.

The topic of business models and the relative economic performance of offsite construction is a relatively new area of research in the United States. The business of offsite construction combines aspects of product- and service-based approaches, especially when it comes to higher value-added systems like enclosed-panel, volumetric modular, and more demanding market segments like multifamily housing. A wide variety of business models currently exist in the U.S. offsite construction sector, with the manufacturer acting as a product supplier to a dealer-builder network being the most common. This business model initially emerged in HUD Code housing to serve a specific segment of the single-family market, but it has expanded to include volumetric modular also focused on single-family detached housing. This model has been challenged by the rapid growth in demand for multifamily housing and other more complex building typologies, with no single best practice dominating. On the other end of the offsite construction spectrum, GCs have started to fabricate open-panel components primarily for use in their own projects and to serve a variety of market sectors.

A systemic issue in offsite construction has been the migration trend toward a more "manufacturing style production system" (borrowing the terminology from the McKinsey Global Institute) by adopting certain means, methods, and technologies from other manufacturing industries without adopting the business models that have made those approaches economically viable and successful (Barbosa et al., 2017). Significant research funding has also supported this type of technology transfer, including digitalization and robotics, without adequate study of the business models that could support it. When these costly technology transfers fail, the established offsite construction industry often retreats to business as usual.

The lack of research focused on the business models of offsite construction is matched with a lack of clear economic performance assessment criteria. Offsite construction systems are often assessed on purely technical terms without considering the business models that support them. Another significant obstacle to the offsite construction industry becoming industrialized is an aversion to data collection and assessment. In other words, *what isn't measured can't be improved,* and it certainly cannot be assessed. Furthermore, what few data are collected are not collected in a consistent manner.

The NIBS OSCC, PTC members, and workshop participants enthusiastically endorsed additional research focused on offsite construction business models and economic performance. Several industry representatives frequently mentioned that no single ideal business model exists for

offsite construction, but a more comprehensive understanding of what models are working and not working would be valuable for the industry. Some participants linked the longstanding public relations (PR) issue of offsite construction to a lack of demonstratable economic performance versus conventional construction.

It became clear during many discussions that the first step in transforming offsite construction into a fully functional manufacturing industry requires developing a data culture. PTC members with U.S. and international experience provided some evidence that more innovative offsite construction companies are moving in this direction, but the transformation is moving too slowly industrywide. Although the U.S. market is unique, participants also agreed that it would be valuable to compare U.S. business models with those in more developed international markets, with emphasis on Japan, Sweden, and the United Kingdom (Scotland), among others.

An array of arguments was presented by participants with respect to how and where a more rigorous culture of economic performance assessment might originate. For some, the offsite construction trade associations were seen as key initiators of this process, whereas others identified developers as key drivers. Several participants with experience in municipal and state programs designed to increase the market penetration of offsite construction supported a federally sanctioned series of pilot programs that could benchmark offsite construction systems. These demonstrations should be considered in context with the markets they serve and the business models and project delivery methods that support them. Additional research is widely supported and required to identify and assess pilot programs that have produced a demonstratable increase in offsite construction adoption and subsequent economic performance at the municipal and state scale in the United States and in more developed international markets (exhibit 20).

Exhibit 20. Offsite Manufactured 3D Volumetric Module Being Craned and Set Into Place from a Truck Bed to Site-Built Foundation for a Single-Family Detached House

Source: MOD X

Business Models and Economic Performance Research Subtopics

Determine a process for the collection and analysis of offsite construction economic performance data.

For an industry to improve, it needs reliable data. There have been many claims about the economic performance of offsite construction—that it is faster, cheaper, safer, stronger, more productive, and sustainable—and although these claims are research-based on case studies, they are representative and not deterministic, meaning they are not definitive. Therefore, there is a critical need to develop a mechanism for the ongoing collection and analysis of offsite construction data. These data may come through existing data sources such as permits at AHJs, transportation permits, a national/state decal program from manufacturers, or perhaps from self-reporting of stakeholders (the latter is not as reliable and is most the difficult for convincing industry professionals to share business performance data). The ongoing need for data will serve to continuously improve the industry and demonstrate offsite construction value to all constituents, including housing developers.

Related Research Questions

- What macro data need to be collected to determine the market share of offsite construction?

- What data fields are required by developers to support business models that utilize offsite construction?
- What consistent data do manufacturers need to continuously improve their products and production process?
- What data are needed by the investment community to determine ROI and performance of the offsite construction sector?
- What is a mechanism to collect these data continuously, analyze them, and make them publicly available for the improvement of offsite construction and to increase the market share?

Identify and assess business models through their related manufacturing, assembly, project delivery, and contractual approaches.

The business models for offsite construction are rapidly changing. Offsite manufacturers are increasing the value-add to their subassemblies and developing new subassemblies or horizontally integrating into different housing sectors (e.g., HUD Code to multi-family). Material product manufacturers and suppliers are interested in migrating down the supply chain and offering more value-add manufacturing of subassemblies. GCs are moving up the value chain to manufacture, and architects are offering value across the delivery of offsite construction (Smith and Rupnik, 2018; Brege, Stehn, and Nord, 2014). In addition to supply chain migration of stakeholders, there are various approaches to self-develop and sell internally, sell to developers, sell to GCs, and sell to dealers. Additional research is required to identify and compile a more comprehensive spectrum of offsite construction business models and assess associated market impacts.

Related Research Questions

- What are the various business models in offsite construction housing delivery that currently exist, and how many companies fit this profile (traditional segmented, horizontal integration, vertical integration, supply chain migration, etc.)?
- What is the impact of various business models on contracts, project delivery, and total value-creation in the development of offsite construction for housing?
- What is the relationship between business models and the development of offsite construction product platforms?
- How are business models impacted by the housing type, the market being served, and the subassemblies to be manufactured and procured?

Assess the cost-value of increased vertical integration.

An essential business model that has demonstrated success internationally is vertical integration—the combining of services and products in the supply chain for greater value creation. Offsite manufacturers in Japan and Sweden have been vertically integrated and offering turnkey delivery and finishing of single-family and multifamily housing for 30 to 40 years. Although there are models of offsite construction vertical integration in the United States, they are currently the exception and not the rule. Additional research is required to assess the cost and value of increasing vertical integration for existing and new entrant players in the offsite construction housing sector to determine if this is an appropriate model for scalable emulation moving forward to realize more affordable and accessible housing. Furthermore, there is a need

for research to determine what steps of vertical supply chain integration will impact the potential return on investment of such integration (Goulding et al., 2014).

Related Research Questions

- What are the defining characteristics of vertical integration, and how are they employed in offsite construction companies in the United States and abroad?
- What are the quantifiable benefits (cost-value) and challenges to vertical integration for offsite construction based on housing type and steps of supply chain integration?
- What are the obstacles to vertical integration companies face for existing offsite construction partners migrating up and down the supply chain and new market entrant start-ups?
- What are alternatives to vertical integration that can have similar project delivery operations and achieve greater project performance (collaborative continuous contracts, joint ventures, etc.)
- How does the manufactured subassembly type impact the ability and success of vertical integration of offsite construction?

Measure the cost-value ratio of increased prefabrication in relation to time and material savings on the job site versus shipping cost.

The degree of completion of subassemblies in the factory is directly related to the value that is created for projects (cost and time). Some building types, contracts, and stakeholder structures are conducive to increased levels of enhancement of subassemblies, while others are less so. Transportation shipping costs increase exponentially with oversized and overweight freight common in offsite manufactured subassemblies and greater distances from the factory to the jobsite. Additional research is required to assess the cost-to-benefit of the degree of enhancement in relation to time and materials savings and shipping costs. This will prove invaluable for decisionmakers, including developers and GCs procuring offsite construction subassemblies, and provide parameters for the appropriate level of finish for delivery models, business models, and building types.

Related Research Questions

- What is the cost-to-benefit ratio of increasing the level of completion of subassemblies during offsite manufacturing, considering the total cost of delivery?
- What is the cost-to-value ratio of level of completion versus transportation distance, cost, and logistics?
- How are the levels of completion and subassembly types related to business models and housing types?

Propose a customer-centric business value across the offsite construction for housing supply chain.

Offsite construction, as a product industry, is ideally centered on the customer. Customer-centric design, manufacture, and assembly are connected to the development of a product platform that, when deployed on projects, provides feedback data to continuously improve the products. Although there have been some nascent efforts from the housing industry to address the need to systematically develop a customer-focused enterprise (Holt, Benham, and Bigelow, 2015), this customer data loop found in other product industries and in the offsite construction industry

internationally (e.g., Sweden, Japan, and Central Europe) has yet to mature in the United States. (Barlow and Ozaki, 2003, 2005). Additional research is required to identify, compile, and assess best practices in customer-oriented product industries and develop a plan to effectively apply these to the U.S. offsite construction housing industry.

Related Research Questions

- What have offsite construction-for-housing customer-centric business models been most successful in more developed international offsite construction industries?
- What are the specific characteristics and moments of customer interface that offsite construction businesses have abroad to provide a personalized solution but manage the number and frequency of customer inputs?
- How are the product platform and subassembly manufacturing related to the customer personalization process in offsite construction companies abroad?
- What examples of customer-centric businesses in other production industries can inform the U.S. offsite construction industry?

Develop an offsite construction, industrywide marketing campaign to communicate the measured benefits.

The social and cultural barriers to offsite construction have mostly been overcome. Two decades ago, offsite construction held a strong stigma as being lower quality compared with traditional construction. The perception from AEC stakeholders have gradually changed from asking "why" engage in offsite construction to asking "what" and "how" offsite construction can be implemented. This is due to the labor conditions and the rising material pricing in the supply-chain that are demanding that developers look at alternative means for housing delivery, and the recent reports from McKinsey that have caught the attention of investors. Despite this progress, remains a social stigma among AEC professionals that offsite construction is more difficult to start. Therefore, there is a need to further communicate the benefits of offsite construction, not as platitudes, but as measured outcomes of cost, schedule, worker safety, environmental performance, etc. Offsite subassembly trade associations have performed their own marketing campaigns for decades, but there is not a singular unified communications effort for offsite construction for housing in the United States that would be impactful as a followup to the findings that result from the research outlined in this report.

Related Research Questions

- What is the value of an industry-wide marketing and communications campaign for offsite construction-for-housing?
- How can this type of communications and marketing effort be organized between the different constituents in offsite construction?
- How can the findings and evidence of offsite construction performance be claimed, collected, and then communicated in an accessible and compelling manner for the general public and AEC professionals to be convinced of the benefits of offsite construction?

4 Conclusion

There is a critical and growing need for housing affordability and supply in the United States. Offsite construction has demonstrated value in achieving cost control, schedule improvements,

and the optimization of labor and environmental performance. Offsite construction has been utilized more frequently, and considerable capital has been invested into offsite manufacturers due to the growth of multifamily demand, a lack of available labor in construction generally, and a need to reduce carbon emissions in building practices and operations. However, there remain considerable barriers that need to be overcome for offsite construction to mature and develop as an industry and supply chain. Although some of these barriers concern technological systems, others are contextual.

The process for identifying research topics in this report did not uncover significant priorities for improving offsite construction technical means and methods, fostering market data, and overcoming social and cultural barriers that continue to limit offsite construction. However, prior surveys and author expertise indicates that these topics need to continue to be developed. The offsite construction research topics and subtopics listed in this report were identified in a consensus process involving the NIBS Offsite Construction Council, literature review, Project Technical Committee (PTC), and workshop participants. This report represents knowledge gaps and research topics to be addressed by HUD PD&R and the industry at large so that offsite construction for housing may be realized at scale.

Some of the offsite construction housing topics can be researched and addressed discretely, but many of the topics are integrally related and sequentially relevant or contingent on one another. The work of the Research Roadmap suggests that the resolution of knowledge gaps in certain topics will be needed to adequately resolve subsequent topics. It is also important to note that each topic will require research and action within the offsite construction industry and within the broader context in which it operates. As such, the topics listed below are given according to suggested priority.

Research Topic Priority 1: Regulatory Framework and Capital, Finance, and Insurance
The regulatory environment and associated industry standards for product certification have significant impacts on innovation and adoption of offsite construction in housing. Operation Breakthrough, PATH, DOE ABC Innovations Roadmap, and international market precedents have taught that regulation and finance need to be addressed prior to the industry growing at scale for housing affordability and access supply concerns. Also, there are considerable challenges with the current financial vehicles for offsite construction for housing development projects and capital investments for offsite manufacturers to increase capacity. These barriers to growth need to be overcome before offsite construction increases in market share and can meet housing needs.

Research Topic Priority 2a: Standards and System Performance
As the offsite construction regulations and finance/capital challenges are addressed, the industry will mature and need to continue to develop standards, best practices, and system performance parameters to help it evolve. Some of these developments can happen concurrently with regulation and finance reform, whereas others will naturally happen as top-priority barriers are alleviated, making way for more innovative offsite construction means of delivery. As the industry progresses, more inventors and innovators will enter the market to offer new and improved solutions for subassemblies and products, requiring the certification process to be more

equitable and accessible. In addition, design, manufacture, and onsite assembly standards will allow for more consistency and predictability in offsite construction delivery.

Research Topic Priority 2b: Project Delivery and Contracts; Labor and Workforce Training and Management; Business Models and Economic Performance
Although not as important as regulatory and finance reform, the development of project delivery and contract standards is just as important as industry standards and system performance. Onsite assembly has been identified as a primary challenge for offsite construction delivery and best practices. Training for design, manufacture, and assembly needs to be assessed and shared so that the offsite construction professionals may improve its performance for developers, financial institutions, and AHJs. One of the greatest needs is onsite assembly training for offsite construction. Current standard contracts were developed without offsite construction considerations and need to be revised. An area that needs study is how various business models (vertical and horizontal integration) affect the performance of offsite construction supply chain companies and what value there is in the migration of supply partners across the value chain.

In addition to topical prioritization, several key takeaways emerged from the roadmap process that can help to frame future research in offsite construction approaches:

Key Takeaway 1: Research is Knowledge-Production and Knowledge-Sharing
Research is the systematic act of discovery of knowledge. Knowledge in construction, including offsite construction, is historically embedded in people and organizations. This implicit knowledge needs to be made explicit and transferred to others in order to mature and develop the offsite construction industry and for innovation to flourish. Research as knowledge-production is therefore the act of generating new knowledge, processes, and products, clarifying existing knowledge, codifying and communicating that knowledge, and continuing the maintenance of the knowledge in a cyclical loop (Anumba, Egbu, and Carrillo, 2007). Although there is a balance that needs to be found between open-access and open-source knowledge and intellectual property, for the offsite construction industry to accelerate its growth and its impact on housing, more knowledge needs to be produced and made available by establishing and promoting a research culture.

Key Takeaway 2: Less Disciplinary Silos, More Interdisciplinary Cross-Cutting Research
Most of the research currently being conducted in the offsite construction sector is focused on means and methods, especially for new technologies. However, most barriers and knowledge gaps identified through this report are situated at the intersection of means and methods internal to the industry and other areas of expertise, including policy, finance, insurance, and labor relations, to name a few. More research is needed to achieve the promise of offsite construction as a more economical, equitable, and ecological form of construction in the areas that define its context: regulatory, finance, standards, workforce, contracts, and business models. This requires not only different disciplinary expertise working in a collaborative manner, but also the involvement of different organizations and institutions—universities, industry, and government—often referred to as the triple helix of innovation (Etzkowitz and Leydesdorff, 1995; Galvao et al., 2019).

It is also recommended that the federal agencies coordinate and collaborate. Federal agencies that may cofund research into the questions identified, and those that operate at the intersection of these topics, include HUD and the following departments:

- The Department of Energy for energy and offsite construction evaluation.
- The General Services Administration and the Department of Defense for government facilities development in housing.
- The United States Department of Agriculture to address lumber supply and development of new wood products.
- The Economic Development Association to help build local economies and communities via offsite construction for housing.
- The Department of Labor to address the growing need for workforce recruitment and training in this evolving offsite construction industry.
- The Department of Transit to answer questions regarding interstate, national, and international transportation and a trade standard for offsite construction.

Furthermore, state and municipal governments can aid in partnering or cofunding these research topics because construction, despite becoming more geographically distributed, is still in many respects a regional affair, especially with regards to housing.

Key Takeaway 3: Data is the Key for Continuous Improvement
An industry is a group of businesses that provide a particular product or service. The businesses are great enough in number to agree upon standards, and they have competition that fosters innovation. Mature industries, especially in manufacturing, gather and analyze market- and business-specific data to quantify performance and to continuously improve performance. Traditional construction does not systematically gather and analyze data. For offsite construction to compete with traditional construction, it must continuously become more industrialized, with data being central to demonstrating value and improvement in order to deliver on its potential.

Key Takeaway 4: Documentation and Dissemination of U.S. Best Practices and Lessons Learned
Although the offsite construction sector is still fragmented in terms of approach, numerous business models, as well as a variety of public initiatives at the municipal, state, and federal levels, are demonstrating impressive results. These programs include zoning revision, finance vehicles, patient capital programs, offsite construction RFPs, etc. Related to data gathering, the performance of these programs, initiatives, and the associated lessons need to be better studied, analyzed, documented, and disseminated.

Key Takeaway 5: Pilot Projects are Key to Demonstration and Adoption
From Operation Breakthrough in the United States to numerous examples in Japan, Sweden, New Zealand, and elsewhere, pilot projects are proving to be effective in demonstrating how to deliver offsite construction. This recommendation is for pilot projects using a “Triple Helix” approach of university, industry, and government to execute and analyze these projects for effectiveness and then document and communicate the results for others to follow. These pilot projects can be technical, but as this report outlines, they should address contextual priority

topics of regulatory and finance early on, with other topics to follow or to be evaluated concurrently.

Key Takeaway 6: Education and Training Are Key for a Secure Knowledgeable Workforce
In most of the topics identified in this report, education and training are clearly needed. In Regulatory Framework, education of local code officials was noted. In Finance and Capital, education for funding institutions and developers seeking finance is needed. Education is also needed to provide resources on access to capital for manufacturers to sustain business operations. The topic of Labor and Workforce focuses on training across the offsite construction supply chain and for new entrants, especially in onsite assembly. Stakeholders need education and training to improve offsite construction project delivery. Education is needed early, often, and throughout offsite construction business and project practices. Furthermore, there is a need to address and fund higher education, trade schools, and apprenticeship programs for increasing jobs and recruiting labor into offsite construction.

Key Takeaway 7: Learn Globally, Act Locally
The PTC's diverse background brought detailed knowledge about the contextual parameters of the U.S. and provided valuable perspectives through their international experiences. The United States is not alone in seeking to improve housing delivery through the use of offsite construction. In the past, U.S. offsite construction programs have served as models for other contexts (i.e., Operation Breakthrough). Offsite construction means and methods, as well as offsite manufactured components and subassemblies, are being exchanged globally. The need for lessons from abroad were identified in nearly every topical area of this report. It is time to develop comparative research projects about international offsite construction programs that bring together industry, academia, and government to improve housing for everyone.

The list of research needs for offsite construction in this report is extensive. This is an industry-wide roadmap. However, some specific findings from this roadmap report are more suited for HUD to address within its interests and capacity. The following list outlines recommendations specifically for HUD to enact as projects, partnerships, and initiatives through research:

- **Knowledge Platform:** Foster a knowledge production, management, and sharing platform for industry, government, and universities to communicate best practices and lessons learned, while also protecting intellectual property.
- **Data Culture:** Create a data collection and analysis process for the offsite construction metrics to both claim the benefits the industry purports and to improve the areas in which it is underperforming as an industry for continuous improvement.
- **Taking Stock:** Support the comprehensive review of Operation Breakthrough, PATH, and other HUD efforts, as well as state and local government initiatives in offsite construction, historically to contemporary, and their individual and collective impact on housing innovation, affordability, and access.
- **Demonstration Projects:** Facilitate and cofund pilot projects for new technologies, policies, finance structures, project delivery/contract structures, and workforce programs for offsite construction to determine their impact and to provide models.
- **Educating AHJs:** Develop an offsite construction education and training program for code officials and other gatekeeping stakeholders.

- **HUD Code:** Investigate the relative merits of the HUD Code versus the ICC codes for potential regulation of manufactured housing.
- **New Products:** Research the obstacles of the current ICC-ES process to innovation and develop mechanisms to foster and expedite new product development in the offsite construction-for-housing sector.
- **Design Standards:** Develop a product platform for affordable and attainable multifamily housing, with standards and specifications that can be shared between manufacturers as a rapid housing initiative to address the housing crisis and homelessness.
- **Supply Chain:** Evaluate the impact of the poor-quality sawn lumber supply chain for offsite manufacturing and develop alternatives. Investigate how offsite manufacturing can help alleviate supply chain issues in housing construction more broadly.
- **Capital:** Work with local and state governments and NGO investors to cofund a patient capital grant or loan program to foster supply-chain migration and start-up funding for offsite manufacturers.
- **Finance:** Partner with Fannie Mae and Freddie Mac to develop a bridge funding vehicle for offsite construction early-stage finance for factory deposits and design documentation assistance associated with offsite construction.
- **Skills and Training:** Support a training and certification program for the offsite construction workforce to improve factory labor practices and onsite assembly quality control and support partnerships with union labor organizations.
- **Vertical Integration:** Research the particulars of vertical integration for offsite construction to determine the benefits, challenges, opportunities, and obstacles and share successful models domestically and internationally for offsite construction.
- **Customer Centric:** Study examples and share best practices of customer-centric enterprise for optimizing a product-based approach to offsite construction for personalization and productivity.
- **Federal Partnerships:** Establish a program to cofund offsite construction for housing research with other federal agencies to rapidly advance knowledge and offsite construction practice and performance.
- **Local Partnerships:** Cofund RFP projects with municipal and state programs to foster offsite construction capacity and capability. Collect and share case studies of local zoning efforts and policy initiatives to foster offsite construction for housing.
- **International Partnerships:** Foster an international network of partners between HUD and offsite construction housing organizations in Japan, Sweden, Australia, the United Kingdom (Scotland), and other parts of Europe for sharing knowledge and cofunding research.

A-1 Appendix A: Research Roadmap Stakeholder Workshop

In December 2021, the National Institute of Building Sciences and MOD X hosted an invite-only, half-day virtual workshop in support of the HUD Industrialized Construction Research Roadmap. The purpose of the workshop was to gather a diverse group of leading experts from across the offsite construction industry to review and validate the proposed research questions and to provide additional areas of recommendation that could be included in the final research roadmap to be published by HUD.

NIBS, MOD X, and PTC Members nominated approximately 70 candidates to invite to the workshop. These candidates were invited based on disciplinary diversity as follows: government, academic, research, consultant, codes and policy, finance, housing and offsite construction advocacy, development, design, engineering, manufacturing, and general contracting/construction management. Over 40 industry experts, representing a diversity of disciplines within the industrialized construction industry, joined HUD, NIBS, MOD X, and the PTC to discuss the proposed research topics. Members of the PTC moderated breakout sessions, each covering one-half of the proposed topics. NIBS and MOD X summarized the workshop discussions for inclusion in the final report. The workshop was conducted via Zoom.

Stakeholder Workshop Attendees
More than 40 attendees participated in the workshop. Their names and affiliations are listed below. HUD, NIBS, and MOD X would like to thank each of the attendees for their participation.

Name	Affiliation	Topics/Notes
Dan Hardcastle	HUD	Federal
Mike Blanford	HUD	Federal
Regina Gray	HUD	Federal
Jagruti Rekhi	HUD	Federal
Kyle Barry	NIBS	Research
Drew Rouland	NIBS	Research
Jiqui Yuan	NIBS	Research
Stephanie Stubbs	NIBS	Research
Ryan Smith	MOD X	Research, Consultant
Ivan Rupnik	MOD X	Research, Consultant
Tyler Schmetterer	MOD X	Research, Consultant
Cindy Davis	State of Virginia; ICC President Board of Directors	Regulatory
Carol Galante	University of California, Berkley Terner Center for Housing	Research
Helena Lidelow	Lindbacks; Lulea University	Manufacturer
Sara Ann Logan	Volumetric Building Companies	Architect and Manufacturer
Cheryn Metzger	PNNL, DOE ABC Collaborative	Research Lab

Lisa Podesto	Lendlease	Developer, GC
Justin Stewart	Synergy Modular	Developer, GC
Margaret Whelan	Whelan Advisory	Investment
Tom Hardiman	MBI / MHBA	Advocacy, Trade
Greg Sloditskie	MBS Consulting	Consultant
Gerry McGaughey	Entekra	Manufacturer
Ryan Colker	ICC	Regulatory
Andrew McCoy	Virginia Tech	Research and Education
Devin Perry	NAHB BSC	Advocacy, Trade
Aundre Oldacre	AoRa Development	Development
Laurie Robert	Horizon North (ret.)	Manufacturer
John Harding	Saint Gobain / Certainteed	Material Supplier
Daniel Stoner	Nex Gen Housing Partners	Developer, GC
Charly Ligety	Housing On Merit	Advocacy, Finance
Nick Gomez	Lowney Architects	Architect
Jeff Speert	4EA Consulting	Envelope Engineer
Harriet Ingham	Home Solutions	Research Lab
Mary Tingerthal	Tingerthal Consulting / Rise Modular	Advocacy, Finance
Craig Mitchell	Black Box Modular	Consultant
Brian Sayre	Buildz	Investment, Manufacturer
Rebecca Lorenz	Assembly OSM	Architect, Manufacturer
Charlie Walls	DPR Construction	GC
Daniel Small	Da Vinci Consulting	Consultant
Diana Fisler	ADL Ventures	Consultant
Alyssa Watson	ADL Ventures	Consultant

Stakeholder Workshop Agenda
The following agenda was developed by NIBS and MOD X to facilitate the stakeholder workshop:

Topic	Time
1. Introduction	11:00am-11:30am
2. Breakout 1: Topics 1-3: Regulatory, Finance/Insurance, Project Delivery/Contracts	11:30am-12:10pm
3. Team Reporting 1	12:10pm-12:30pm
4. Break	12:30pm-12:40pm
5. Breakout 2: Topics 4-6: Workforce/Labor, Business/Value Proposition, Standards	12:40pm-1:20pm
6. Team Reporting 2	1:20pm-1:40pm

7. Final Summary

1:40pm-2:00pm

Kyle Barry from the National Institute of Building Sciences facilitated the workshop and managed the virtual platform. During the Introduction, Dan Hardcastle, Special Assistant for Special Projects, Office of the Secretary from HUD, provided introductory remarks. Ryan Smith from MOD X then provided background on the research roadmap and the purposes of the workshop.

The workshop had two breakout sessions with subsequent report-outs, each facilitated by the PTC members. For each breakout session, attendees were divided into four groups (each made up of approximately 11 participants) to discuss one-half of the proposed research topics. PTC members moderated the small group discussions, with a member of MOD X or NIBS providing notes. Following the breakout, the PTC provided a report-out to the larger participant group. This process, with the same group, was repeated during the second breakout during which the second half of research topics were discussed.

Following the breakout sessions, Ryan Smith of MOD X provided a final summary of the workshop findings and presented the roadmap schedule to participants. The workshop was then adjourned.

A-2 Appendix B: References

AGC ConsensusDocs 753. 2020. Standard Prefabricated Construction Agreement Between Constructor and Prefabricator. https://www.consensusdocs.org/contract/753-2/.

Ahn, S., L. Crouch, T.W. Kim, and R. Rameezdeen. 2020. "Comparison of Worker Safety Risks Between Onsite and Offsite Construction Methods: A Site Management Perspective," *Journal of Construction Engineering and Management*, 146 (9): 05020010.

Aitchison, Mathew. 2017. "A House is Not a Car (Yet)," *Journal of Architectural Education* 71 (1): 10–21.

Al-Hussein, M. (no date). *Journal of Industrialized Construction*. https://journalofindustrializedconstruction.com/index.php/jic/index.

Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M., Sridhar, M., Parsons, M., Bertram, N., and Brown, S. 2017. Reinventing Construction Through a Productivity Revolution. McKinsey Global Institute. February 2017. https://www.mckinsey.com/business-functions/operations/our-insights/reinventing-construction-through-a-productivity-revolution.

Barlow, James, and Ritsuko Ozaki. 2005. "Building Mass Customised Housing Through Innovation in the Production System: Lessons from Japan," *Environment and Planning A,* 37 (1): 9–20.

Barlow, James, and Ritsuko Ozaki. 2003. "Achieving 'Customer Focus' in Private Housebuilding: Current Practice and Lessons from Other Industries," *Housing Studies* 18 (1), 87–101.

BC Housing. 2021. Rapid Housing Initiative for Homelessness. BC Housing and Vancouver Affordable Housing Agency. https://www.bchousing.org/projects-partners/Building-BC/RRH.

Benson, T. 2008. Keynote: Adventures in Prefabrication. Without A Hitch: New Directions in Prefabricated Architecture. ACSA Fall Conference 2008. https://scholarworks.umass.edu/cgi/viewcontent.cgi?article=1001&context=wood.

Oshima, Ken Tadashi, and Rasmus Waern. 2008. *Home Delivery: Fabricating the Modern Dwelling*, edited by Barry Bergdoll and Peter Christensen. New York: The Museum of Modern Art.

Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., & Woetzel, J. (2019). Modular construction: From projects to products. *McKinsey & Company: Capital Projects & Infrastructure*, 1-34.

Brege, Staffan, Lars Stehn, and Thomas Nord. 2014. "Business Models in Industrialized Building of Multi-Storey Houses," *Construction Management and Economics* 32 (1–2): 208–226.

Bruce, Alfred, and Harold Sandbank. 1945. *A History of Prefabrication*. Raritan, NJ, John B. Pierce Foundation.

Buntrock, Dana. 2017. "Prefabricated Housing in Japan. In Offsite Architecture: Constructing the Future. Edited by Ryan E. Smith and John D. London; New York: Routledge, Taylor & Francis Group: 203–226.

Carlisle, Rodney P. 2009. *Handbook to Life in America. Volume VIII, Postwar America, 1950 to 1969.* New York, NY: Facts on File. ISBN 978-1-4381-2699-9.

Anumba, Chimay J, Charles Egbu, and Patricia Carrillo, eds. 2005. *Knowledge Management in Construction*. Hoboken, New Jersey: Wiley Blackwell.

Court, Peter F., Christine L. Pasquire, G.F. Gibb, and David Bower. 2009. "Modular Assembly with Postponement to Improve Health, Safety, and Productivity in Construction," *Practice Periodical on Structural Design and Construction* 14 (2): 81–89. https://doi.org/10.1061/(ASCE)1084-0680(2009)14:2(81).

Darnall, M. J. 1972. "Innovations in American Prefabricated Housing: 1860–1890," *The Journal of the Society of Architectural Historians* 31 (1): 51–55.

Davies, Alex. 2018. "Modern Methods of Construction: A Forward-Thinking Solution to the Housing Crisis?" Royal Institution of Chartered Surveyors (RICS). https://www.rics.org/globalassets/rics-website/media/news/news--opinion/modern-methods-of-construction-paper-rics.pdf.

Davis, Daniel. 2021. "Katerra's $2 Billion Legacy," *Architect Magazine*. June 18. https://www.architectmagazine.com/technology/katerras-2-billion-legacy_o.

Deakin, Mark, Luca Mora, Alasdair Reid, Robert Hairstans, Mila Duncheva, Carola Calcagno, Madeline Smith, Paul Smith, and Vanessa Lang. 2020. *Increasing Offsite Housing Construction in Scotland: An Evidence Base to Support New Policy and Systems.* Blantyre, Scotland: Construction Scotland Innovation Centre. https://www.cs-ic.org/library/increasing-offsite-housing-construction-in-scotland-an-evidence-base-to-support-new-policy-and-systems/.

Dineen, J.K. 2020. "San Francisco Trade Unions at Odds Over Modular Construction," *San Francisco Chronicle*. December 13. https://www.sfchronicle.com/bayarea/article/San-Francisco-trade-unions-at-odds-over-modular-15755264.php.

DOE ABC. 2021. Advanced Building Construction Initiative. Department of Energy. https://www.energy.gov/eere/buildings/advanced-building-construction-initiative.

Ebbers, Joris J., and Nachoem M. Wijnberg. 2009. "Latent Organizations in the Film Industry: Contracts, Rewards and Resources," *Human Relations* 62 (7): 987–1009.

Eisenberg, David, Robert Done, and Loretta Ishida. 2002. Breaking Down the Barriers: Challenges and Solutions to Code Approval of Green Building. Development Center for Appropriate Technology Report, 2002. https://www.researchgate.net/publication/237290711_Breaking_Down_the_Barriers_Challenges_and_Solutions_to_Code_Approval_of_Green_Building.

ESCO. 2022. European Construction Sector Observatory. https://ec.europa.eu/growth/sectors/construction/observatory_en Accessed.

Fannie Mae. 2020. Multi-Family Modular Construction Toolkit. Fannie Mae. https://multifamily.fanniemae.com/media/13576/display.

FMI. 2018. New Day, New Mindset—Rethinking Offsite Construction: 2018. FMI/CURT/CII Owner Survey. FMI. https://fmicorp.com/insights/industry-insights/2018-fmi-curt-cii-owner-survey/.

Foliente, Greg C. 2000. "Developments in Performance-Based Building Codes and Standards," *Forest Products Journal* 50 (7/8): 12–21.

Freedonia. 2021. *Global Prefabricated Housing—Demand and Sales Forecasts, Market Share, Market Size, Market Leaders*. Study: 3971. https://www.freedoniagroup.com/World-Prefabricated-Housing.html. Cleveland, OH: The Freedonia Group.

Gann, David M. 1996. "Construction as a Manufacturing Process? Similarities and Differences Between Industrialized Housing and Car Production in Japan," *Construction Management Economics* 14 (5): 437–450.

Gao, Shang, Ruoyu Jin, and Weisheng Lu. 2020. "Design for Manufacture and Assembly in Construction: A Review," *Building Research & Information* 48 (5): 538–550.

Global Industry Analysts, Inc. 2021. Prefabricated Buildings—World Market Report. https://www.strategyr.com/market-report-prefabricated-buildings-forecasts-global-industry-analysts-inc.asp.

Goulding, J.S., F. Pour Rahimian, M. Arif, and M.D. Sharp. 2014. "New Offsite Production and Business Models in Construction: Priorities for the Future Research Agenda," *Architectural Engineering and Design Management* 11 (3): 163–184.

Goulding, J.S., and M. Arif. 2013. Research Road Map Report: Offsite Production and Manufacturing, Publication 372, International Council for Research and Innovation in Building and Construction. https://site.cibworld.nl/dl/publications/pub_372.pdf.

Haas, C.T., J.T. O'Connor, R.T. Tucker, J.A. Eickmann, and W.R. Fagerlund. 2000. *Prefabrication Preassembly Trends and Effects on the Construction Workforce. Rep. No. 14.* Austin, TX: Center for Construction Industry Studies.

Habraken, J, J.T. Boekholt, A.P. Thyssen, P.J.M. Dinjens. 1974. *Variations, the Systematic Design of Supports,* English translation by W. Wiewel and Sue Gibbons. Cambridge, MA: MIT Press.

Habraken, N. John. 1972. *Supports: An Alternative to Mass Housing,* London: Urban International Press 1972.

Hairstans, Robert. 2015. *Building Offsite: An Introduction. Architecture and Design Scotland.* http://www.ads.org.uk/wp-content/uploads/Building-Offsite-An-Introduction.pdf.

Hairstans, Robert, and Fausto Sanna. 2017. "A Scottish Perspective on Timber Offsite Construction." In *Offsite Architecture: Constructing the Future*, edited by Ryan E. Smith and John D. Quale. London, United Kingdom: Routledge: 236–264.

Hairstans, Robert, and T. Duncheva. 2020. "Core Offsite Manufacture Industry Drivers." In *Offsite Production and Manufacturing for Innovative Construction: People, Process and Technology*, edited by Jack S. Goulding and Farzad Pour Rahimian. Routledge: 257–284.

Hall, Robert W and Yoshinori Yamada. 2008. "Tokyo Sekisui Routinely Builds 80 Percent of a House in Three Days," *Target Magazine*, Association for Manufacturing Excellence (AME) https://www.ame.org/sites/default/files/documents/08-24-2-Sekisui.pdf.

Hall, Thomas, and Sonja Vidén. 2005. "The Million Homes Programme: A Review of the Great Swedish Planning Project," *Planning Perspectives* 20 (3): 301–328. DOI: 10.1080/02665430500130233.

Harland, Peter E., Zakir Uddin, and Sven Laudien. 2020. "Product Platforms as a Lever of Competitive Advantage on a Company-Wide Level: A Resource Management Perspective," *Review of Managerial Science* (14): 137–158.

Henderson, Tim. 2019. "Rural America Faces a Housing Crunch." The Pew Charitable Trusts. https://www.pewtrusts.org/en/research-and-analysis/blogs/stateline/2019/03/25/rural-america-faces-a-housing-cost-crunch

HIA. 2022. "Off-Site Heat Map: Production Housing Heat Map of Off-Site Construction Service Providers." Housing Innovation Alliance. https://www.housinginnovationalliance.com/tools-resources/off-site-heat-map/

Holt, Eric A., James M. Benham, and Ben Fitzgerald Bigelow. 2015. "Emerging Technology in the Construction Industry: Perceptions from Construction Industry Professionals." In 2015 ASEE Annual Conference & Exposition: 26–595.

ICC. 2018. "2018 ICC Performance Code for Buildings and Facilities (ICCPC)." https://codes.iccsafe.org/content/ICCPC2018/preface.

ICC. 2020. “FAQs on Off-site Construction. International Code Council.” https://www.iccsafe.org/wp-content/uploads/20-19332_GR_Offsite_Construction_FAQs_FLR_FINAL1_HIRES.pdf Accessed 3/14/22.
ICC (2022). Off-site Construction Toolkits. https://www.iccsafe.org/advocacy/safety-toolkits/offsite-construction/.

ICC NTA. 2020. “Visual Cues: Inside NTA’s First All-Virtual Modular Plant,” *Building Safety Journal*. International Code Council. https://www.iccsafe.org/building-safety-journal/bsj-dives/visual-cues-inside-icc-ntas-first-all-virtual-modular-plant-inspection/.

ICC-ES. 2022. “ICC Evaluation Service.” https://icc-es.org/.

ICC/MBI. 2021. “ICC/MBI 1200-2021 Standard for Off-Site Construction: Planning, Design Fabrication and Assembly.” International Code Council. https://shop.iccsafe.org/standards/icc-mbi-1200-2021-standard-for-off-site-construction-planning-design-fabrication-and-assembly.html.

ILO. 2005. *Prevention: A Global Strategy: Promoting Safety and Health at Work. International Labor Organization 2005.* Geneva, Switzerland. https://www.ilo.org/moscow/information-resources/publications/WCMS_312123/lang--en/index.htm.

Ivory Innovations. 2020. “Ivory Prize and Hack-A-House Focus Areas.” https://ivory-innovations.org/.

Jensen, Patrik, Helena Lidelow, and Thomas Olofsson. 2015. “Product Configuration in Construction,” *International Journal of Mass Customisation* 5 (1) Inderscience Enterprises Ltd: 73–92.

Joint Center for Housing Studies of Harvard University. 2016. “Housing Challenges, The State of the Nation's Housing 2016.” http://www.jchs.harvard.edu/sites/jchs.harvard.edu/files/son_2016_200dpi_ch6.pdf.

JPCSMA. 2022. “Japanese Prefabricated Construction Suppliers and Manufacturers Association.” https://www.purekyo.or.jp/bukai/jyutaku/english/index.html.

Kelly, Burnham. 1951. *The Prefabrication of Houses*. Cambridge, MA: Technology Press of the Massachusetts Institute of Technology and New York: Wiley.

Ku, Kihong, and Paul Broadstone. 2017. “A Case Study of Multi-Trade Near-Site Factory Assembly.” In *Offsite Architecture: Constructing the Future*, edited by Ryan E. Smith and John D. Quale. London, United Kingdom: Routledge: 174–189.

Lessing, Jerker. 2006. *Industrialised House-Building: Concepts and Processes*. Division of Design Methodology. Lund University, Lund 2006. http://www.caad.lth.se/fileadmin/projekteringsmetodik/publications/Lessing_lic-webb.pdf.

Lessing, Jerker, and Staffan Brege. 2018. “Industrialized Building Companies’ Business Models: Multiple Case Study of Swedish and North American Companies,” *Journal of Construction Engineering and Management,* 144(2), 05017019.

Lidelow, H. 2017. “Offsite Construction in Sweden: From Technology to Integrated Process In *Offsite Architecture: Constructing the Future*, edited by Ryan E. Smith and John D. Quale. London, United Kingdom: Routledge: 226–236.

Lu, Weisheng, Tan, Jinying Xu, Jing Wang, Ke Chen, Shang Gao, and Fan Xue. 2021. “Design for Manufacture and Assembly (DfMA) in Construction: The Old and the New,” *Architectural Engineering and Design Management*, 17 (1-2): 77–91.

Magdiel Pérez-Lara, Jania Astrid Saucedo-Martínez, José Antonio Marmolejo-Saucedo,Tomás Eloy Salais-Fierro, and Pandian Vasant. 2020. “Vertical and Horizontal Integration Systems in Industry 4.0,” *Wireless Networks* 26: 4767–4775. https://doi.org/10.1007/s11276-018-1873-2.

Manley, Karen, and Kristian Widén. 2019. “Prefabricated Housing Firms in Japan and Sweden: Learning from Leading Countries.” In *Offsite Production and Manufacturing for Innovative Construction—People Process, and Technology*, Taylor & Francis: 399–418.

Market Research Future. 2020. Prefabricated Buildings Market Overview. https://www.marketresearchfuture.com/reports/prefabricated-buildings-market-5171.

Martin, T. n.d. “All You Need to Know About Modularization.” https://www.modularmanagement.com/blog/all-you-need-to-know-about-modularization.

Matsumura, Shuichi. 2004. “Prefabricated House-Building Systems in Japan.” In *10. Internationales Holzbau-Forum 2004* (Hochschule für Architektur, Bau und Holz (HSB), Biel, 2004).

Matsumura, Shuichi. 2006. “How Have CAD-CAM Systems Changed Japanese Conventional Wooden Construction in These Three Decades?” in *2006 Proceedings of the 23rd ISARC*, Tokyo, Japan.

Matsumura, Shuichi, Tomoyuki Gondo, Kouichi Sato, Yoshiro Morita, and Toru Eguchi. 2018. Technological Developments of Japanese Prefabricated Housing in an Early Stage,” *Japan Architectural Review* 2 (1) 52–61.

MBI. 2021. 2021 *Permanent Modular Construction Report*. Modular Building Institute. https://www.modular.org/industry-analysis/.

MBI. 2022. “Breaking Down the ‘Modular Building Code.’” Modular Building Institute. https://www.modular.org/2020/02/03/breaking-down-the-modular-building-code/.

MCCB. 2017. *Handbook for the Design of Modular Structures*. Modular Construction Codes Board. Monash University, Australia. https://www.dropbox.com/s/dvzf0fg3p8lwdsh/Handbook%20for%20the%20Design%20of%20Modular%20Structures.pdf?dl=0= Accessed 3/14/2022.

McCutcheon, R.T. 1992. "Science, Technology and the State in the Provision of Low-Income Accommodation: The Case of Industrialized House-Building, 1955–77," *Social Studies of Science* 22 (2): 353–371.

MHI. 2021. Manufactured Home Monthly Shipments 1976–2021. Modular Housing Institute. https://www.manufacturedhousing.org/wp-content/uploads/2020/05/1-UPDATED-MH-Monthly-Shipments-1976-2019.pdf.

MOD X. 2021. Virtual X. http://modx.network.

Muffatto, Moreno, and Marco Roveda. 2002. Product Architecture and Platforms: A Conceptual Framework," *International Journal of Technology Management,* 24 (1): 1–16.

NRC. 2009. Advancing the Competitiveness and Efficiency of the U.S. Construction Industry. National Research Council. 2009: 1.

NRC. 2008. Rebuilding the Research Capacity at HUD: Chapter 4 Evaluation of Technology Research. National Research Council: 65–78.

Nutt-Powell, T.E. 1985. "The House that Machines Built," *Technology Review* 88 (8): 31–37.

Oakland. 2021. Oakland City Planning Commission. Agenda Report. Case File Number ZA21013. June 2. https://oaklandside.org/wp-content/uploads/2021/06/03-Staff-Report-Planning-Commission-6-2-21-Construction-Innovation-Ordinance-Item-3.pdf.

Oster, Sharon M., and John M. Quigley. 1977. "Regulatory Barriers to the Diffusion of Innovation: Some Evidence from Building Codes," *The Bell Journal of Economics* 8 (2): 361–377.

Pan, Wei, Alistair G.F. Gibb, and Andrew R.J. Dainty. 2012. "Strategies for Integrating the Use of Off-Site Production Technologies in House Building," *Journal of Construction Engineering and Management,* 138 (11): 1331–1340.

Patman, Philip, E. Jay Howenstine, Charles Szczepanski, Jack Warner. 1968. *Industrialized Building: A Comparative Analysis of European Experiences.* Prepared for the Office of International Affairs of the U.S. Department of Housing and Urban Development, distributed by Clearinghouse for Federal and Scientific Information (PB 179 069). Washington, D.C: U.S. Department of Commerce/National Bureau of Standards.

Perera, Srinath, Samudaya Nanayakkara, M.N.N. Rodrigo, Sepani Senaratne, and Ralf Weinand. 2020. “Blockchain Technology: Is it Hype or Real in the Construction Industry?” *Journal of Information Integration* 17: 100125. https://doi.org/10.1016/j.jii.2020.100125.

Perman, K. 2011. *Swedish Building Policy and the Manufacturers of Single-Family Houses in the Country of Dalarna. A Collaboration for the Future Goal of the Improvement of Energy Efficiency?* Presented at the World Renewable Energy Congress 2011—Sweden. 8–13 May 2011, Linkoping, Sweden. https://ep.liu.se/ecp/057/vol10/041/ecp57vol10_041.pdf.

Perry, Martin K. 1989. Vertical integration: Determinants and Effects. In *Handbook of Industrial Organization,* Vol. 1, 1989. Amsterdam: Netherlands: Elsevier: 183–255.

Pless, Shanti, Stacy K. Rothgeb, Ankur Podder, and Noah Klammer. 2020. Integrating Energy Efficiency into the Permanent Modular Construction Industry [Slides]. United States: N. p., 2020. Web. doi:10.2172/1598138.

Pons-Valladares, O., and G. Wadel. 2011. “Environmental Impacts of Prefabricated School Buildings in Catalonia,” *Habitat International* 2011 (35): 553–563.

Quale, John, Matthew J. Eckelman, Kyle Williams, Greg Sloditskie, and Julie B. Zimmerman. 2012. “Construction Matters: Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States,” *Journal of Industrial Ecology* 16 (2): 243–254.

Raskin, W. and Bennet, E. 1936. “48 Systems of Prefabrication,” *American Art and Architecture* CLXIX (No. 2649, September 1936).

Richardson, T.M. 2018. “Operation Breakthrough.” https://www.huduser.gov/portal/pdredge/pdr-edge-frm-asst-sec-030518.html.

Rupnik, I. 2015. “Projecting in Space-Time: The Laboratory Method, Modern Architecture and Settlement-Building, 1918–1932.” Doctoral dissertation, Graduate School of Arts & Sciences, Harvard University.

Rupnik, I. 2017. “Mapping the Modular Industry.” In *Offsite Architecture: Constructing the Future*, edited by Ryan E. Smith and John D. Quale. London, United Kingdom: Routledge: 70–91.

Rupnik, I. 2019. “The Geographies of Industrialized Wood-based Construction for Mass Housing,” *Wood Design Focus* 29 (1) Spring 2019. Forest Products Society: 3–9.

Rupnik, I. and R.E. Smith. 2018. “The Modular Industry in North America.” In *Prefab Housing and the Future of Building: Process and Product.* Edited by M. Aitchison. London, United Kingdom: Lund and Humpries.

Schuh, Günther, Michael Riesener, Sebastian Barg and Lauf Hendrik. 2017. Methodology for the Contextual Design of a Modular Product Platform Concept. *Proceedings of the 21st*

International Conference on Engineering Design (ICED17), The University of British Columbia, Vancouver, Canada, 21–25 August 2017. https://www.designsociety.org/download-publication/39605/Methodology+for+the+contextual+design+of+a+modular+product+platform+concept.

Sisson, Patrick. 2018. "Construction Industry, Mid Boom, Can't Find Enough Skilled Workers," *Curbed*. https://archive.curbed.com/2018/1/23/16910310/construction-homebuilding-labor-shortage-jobs-vocational-training.

Smith, Ryan E. 2016. Off-Site and Modular Construction Explained. National Institute of Building Sciences.

Smith, Ryan E., Massih Nilforoushan Hamedani, and Gentry Griffin. 2018. "Developing Timber Volume Calculators Through a Comparative Case Study Analysis of Wood Utilization in On-Site and Off-Site Construction Methods," *Technology| Architecture+ Design,* 2 (1): 55–67.

Smith, Ryan E. 2018. Off-Site Construction Industry Survey 2018. May 2018. National Institute of Building Sciences. https://cdn.ymaws.com/www.nibs.org/resource/resmgr/oscc/oscc-2018surveyreport.pdf.

Smith, Ryan E. 2009. History of Prefabrication: A Cultural Survey. In *3rd Annual International Congress on Construction History*. Cottbus, Germany May 20–24, 2009. Pg. 1355–1364. ISBN 978-3-936033-31-1.

Smith, Ryan E. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken: John Wiley & Sons, Inc.

Smith, Ryan E. 2015. Off-Site Construction Industry Survey 2014. May 2015. National Institute of Building Sciences.
http://www.nibs.org/resource/resmgr/OSCC_NIBS_OSCC_2014Survey.pdf.

Smith, Ryan E. 2019. "Mass Prefabrication: Investigating the Relationship Between Prefabrication and Mass Customization in Architecture." In *Mass Customization and Design Democratization,* edited by Branko Koleravic and José Pinto Duarte. London, United Kingdom and New York: Routledge.

Smith, Ryan E., and John D. Quale, eds. 2017. *Offsite Architecture: Constructing the Future.* London, United Kingdom: Routledge.

Smith, Ryan E., and T. Rice. 2015a. Permanent Modular Construction: Products Process and Performance. Modular and Off-site Construction Summit 2015, Edmonton, Alberta, May 2015.

Smith, Ryan E., and T. Rice. 2015b. Business Strategies in Prefabricated Housing. Integrated Technology in Architecture Center. University of Utah.

Smith, Ryan E., and I. Rupnik. 2018. 5 in 5 Modular Growth Initiative: Research Roadmap Recommendations. Modular Building Institute.

Smith, Ryan E., and I. Rupnik. 2020. "Productivity Innovation and Disruption: Offsite Construction in the U.S." In *Offsite Production and Manufacturing for Innovative Construction: People, Process and Technology*, edited by Jack S. Goulding and Farzad Pour. United Kingdom: Routledge.

Smith, Sean, Robert Hairstans, Russell MacDonald, and Fausto Sanna. 2013. Strategic Review of the Offsite Construction Sector in Scotland. The Scottish Government. ISBN 978-1-78256-394-5

Specialized Carriers and Rigging Association (SC&RA). 2021. Uniform Permit Transport 2021. https://www.scranet.org/SCRA/Content/advocacy/OS-OW-Permitting.aspx

Staats, E. 1976. Operation Breakthrough: Lessons Learned About Demonstrating New Technology. U.S. Government Accountability Office. https://www.gao.gov/assets/120/117465.pdf.

Storm, P. 2022. Operation 2030: Scaling Building Decarbonization in Washington State. White Paper 2022. Clean Energy Transition Institute. https://uploads-ssl.webflow.com/5d8aa5c4ff027473b00c1516/61d7a479ba34328152be6239_CETI-2050%20Institute%20Operation%202030%20White%20Paper_2022-01-05.pdf.

Tam, Vivian W.Y., and C.M. Tam. 2006. A Review on the Viable Technology for Construction Waste Recycling, *Resources, Conservation and Recycling* 47 (3): 209–221. doi:doi:10.1016/j.resconrec.2005.12.002

Temkin, Kenneth, Grace Hong, Laurel Davis, Ed Hudson, and Randall Cantrell. 2007. *Factory-Built Construction and the American Homebuyer: Perceptions and Opportunities.* Prepared for the U.S. Department of Housing and Urban Development, Office of Policy Development & Research (HUD-PD&R). Washington, DC: HUD.

The Housing Lab. 2020. Terner Center UC Berkeley Housing Lab. https://www.housinglab.co/.

Tomohiro, H. 2013. *Introduction to the Building Standard Law: Building Regulation in Japan. Ver. July 2013.* Toyo, Japan: Building Center of Japan. https://www.bcj.or.jp/upload/international/baseline/BSLIntroduction201307_e.pdf.

U.S. Bureau of Labor Statistics. 2009. Census of Fatal Occupational Injuries 2008. U.S. Bureau of Labor Statistics. http://www.bls.gov/iif/oshwc/cfoi/cftb0240.pdf.

U.S. Department of Housing and Urban Development. 2020. Guidelines for Preparing a Report for Publication. Research Utilization Division, Office of Policy Development and Research. July 2020. https://www.huduser.gov/portal/About/style-guide-for-reports.pdf.

U.S. Department of Housing and Urban Development. 2021. “PATH Roadmaps.” Washington, DC: U.S. Housing and Urban Development, Office of Policy Development and Research (PD&R). https://www.huduser.gov/portal/PATH-Roadmaps.html.

U.S. Department of Housing and Urban Development, Office of Policy Development and Research (HUD-PD&R). 2021. Washington, DC: U.S. Housing and Urban Development, Office of Policy Development and Research (PD&R) https://www.huduser.gov/portal/sites/default/files/pdf/NationalSummary-3Q21.pdf.

Woetzel, Jonathan, Sangeeth Ram, Jan Mischke, Nicklas Garemo, and Shirish Sankhe. 2014. A Blueprint for Addressing the Global Housing Challenge. McKinsey Global Institute. https://www.mckinsey.com/~/media/mckinsey/featured%20insights/urbanization/tackling%20the%20worlds%20affordable%20housing%20challenge/mgi_affordable_housing_executive%20summary_october%202014.ashx.

Weston, T. 2016. Alternate Means and Materials for Code Compliance. http://media.iccsafe.org/Annual/2016/Alternate-Means-and-Materials-for-Code-Compliance.pdf.

Wilson, J. 2019. Design for Modular Construction: An Introduction for Architects. American Institute of Architects and the National Institute of Building Sciences. http://content.aia.org/sites/default/files/2019-03/Materials_Practice_Guide_Modular_Construction.pdf.

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