BRINGING DIGITALIZATION HOME SYMPOSIUM

Modularization Precedes Digitalization in Offsite Housing Delivery

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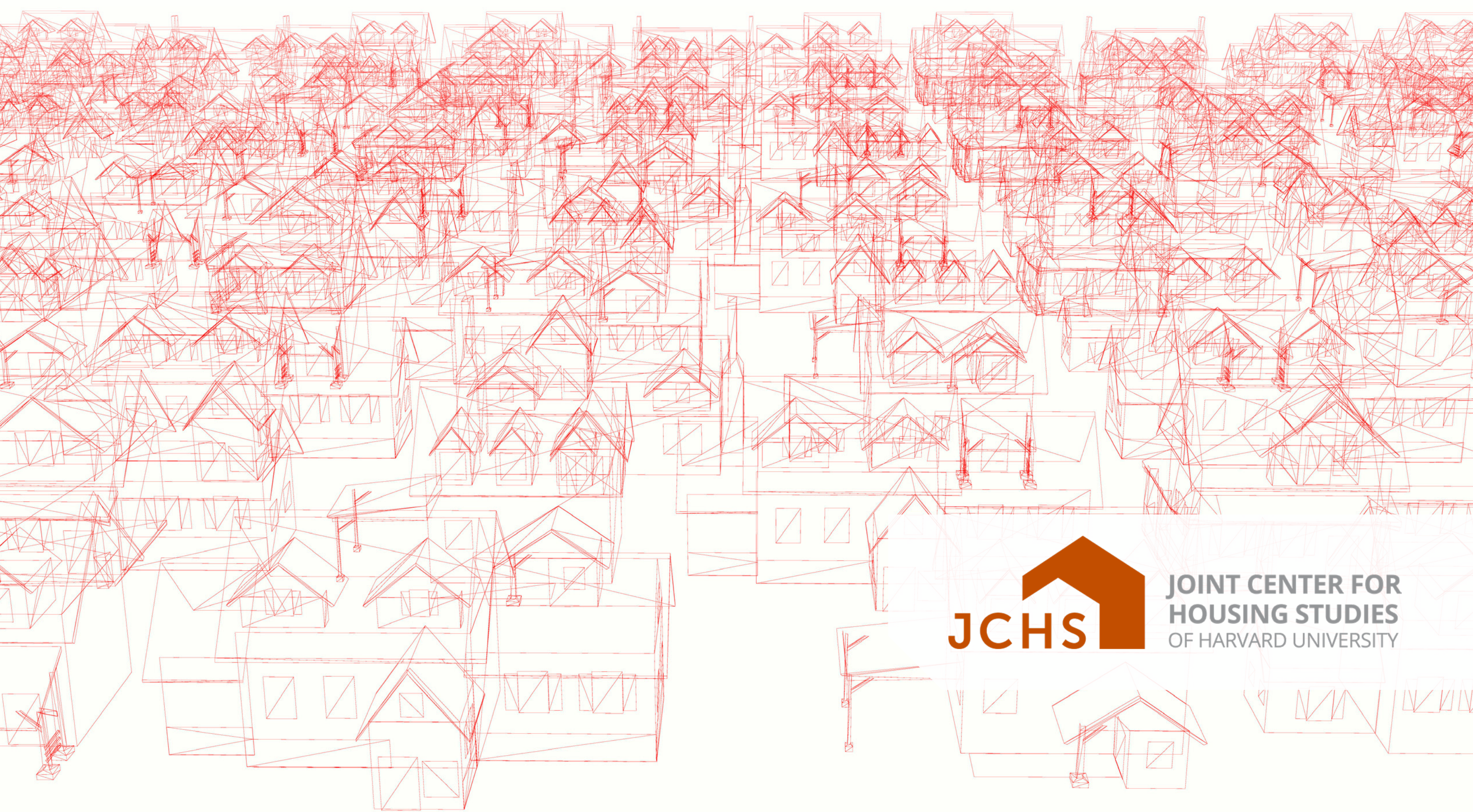

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Modularization Precedes Digitalization in Offsite Housing Delivery

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Introduction

For much of the twentieth century, architects, builders, developers, economists, and policymakers have pursued the "dream of the factory-made house".[1] The hope was that the progressive industrialization of housing would result in a similar combination of quality, speed, and economy that historically revolutionized many other industries, including agriculture and manufacturing. US builders successfully industrialized onsite wood-based construction during the postwar period; they focused primarily on detached single-family production housing, increased productivity, and affordability. Since 1968, US construction has effectively *deindustrialized,* favoring manual labor over digitalization and mechanization to mitigate the unpredictable risk associated with market volatility.[2] In 2017, the McKinsey Global Institute claimed that US construction labor productivity has declined by an average of 1.7% annually since 1968, while nearly every other sector of the economy—including manufacturing, retail, and agriculture—has grown by as much as 1,500% since 1945. This growth has occurred largely through the ongoing adoption and application of new technologies.[3]

Why has construction not experienced productivity gains associated with industrialization while vast economic opportunity costs continue to accrue? Mechanized means and methods of construction have existed for the better part of the last century in the US construction sector. Like many other industrialized economies, the US attempted to increase offsite market share through a demonstration program, US Department of Housing and Urban Development's (HUD) Operation Breakthrough. Initially considered a failure, the program nevertheless created much of the regulatory framework within which US offsite construction operates today.[4] Digitalization tools—including Computer-Aided Design and

[1] Herbert, *The Dream of the Factory-Made House*. For a more recent overview of the relationship between architecture and offsite construction, see Smith, *Prefab Architecture*.

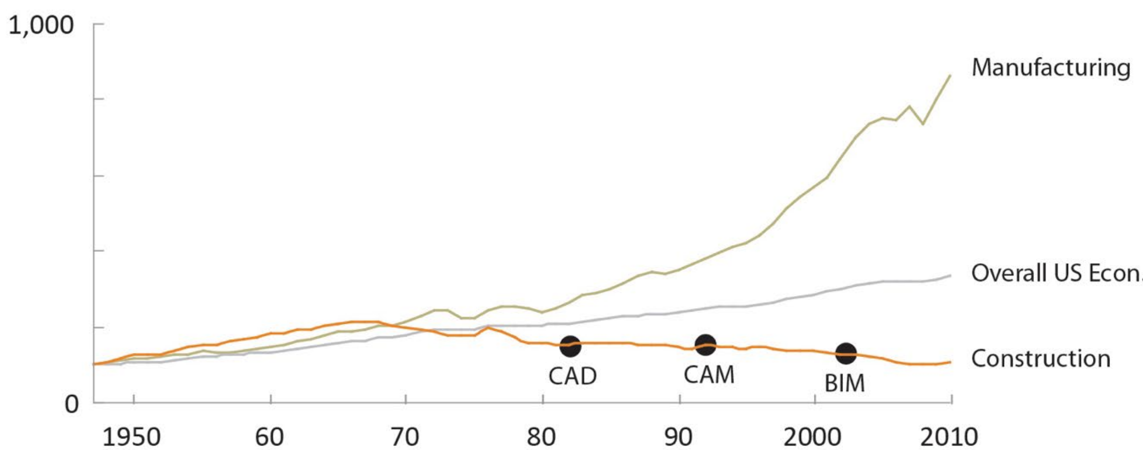
[2] The construction industry's productivity loss and deindustrialization were identified in Barbarosa, et al., *Reinventing Construction.* A series of articles in *The Economist* followed that included, "Efficiency eludes the construction Industry" and "The Construction Industry's Productivity Problem," both of which include additional data not included in the report.

[3] Barbarosa, et al., *Reinventing Construction*, 23.

[4] HUD initiated Operation Breakthrough to "demonstrate the value of industrialized (factory-built) housing construction methods" and to "eliminate or reduce barriers to industrialized housing construction." While the program was not successful at demonstrating the value of twenty-two (22) new industrialized building systems, it did have a lasting impact on the regulatory framework of US construction and paved the way for national and state building codes that until that time were primarily municipal or regionally based. Moreover, the demonstration program led to a nationwide regulation of the existing manufactured housing industry via the "HUD Code" in 1976 and provided a standard for the transportation of other offsite construction systems, including panelized and volumetric modular subassemblies. One of the most thorough assessments of the program is included in Elmer, *Operation Breakthrough*. MOD X and the National Institute for Building Science (NIBS) are currently working with HUD to assess the impact of Operation Breakthrough on the current US offsite construction industry to better understand how the regulatory framework can evolve in the future.

Drafting (CADD), Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) and Building Information Modeling (BIM)—regularly introduced to support the architecture, engineering, and construction (AEC) industry over the past sixty years have become widely available. Despite these efforts to create a regulatory framework more amenable to offsite construction and the continued development of hardware and software technologies for the construction sector, labor productivity has continued to decrease and the cost of construction of housing has increased.[5]

Figure 1: Construction Productivity Performance in the US (1950 – 2010)



Data Source: Adapted from Barbarosa, et al., *Reinventing Construction*, 23.

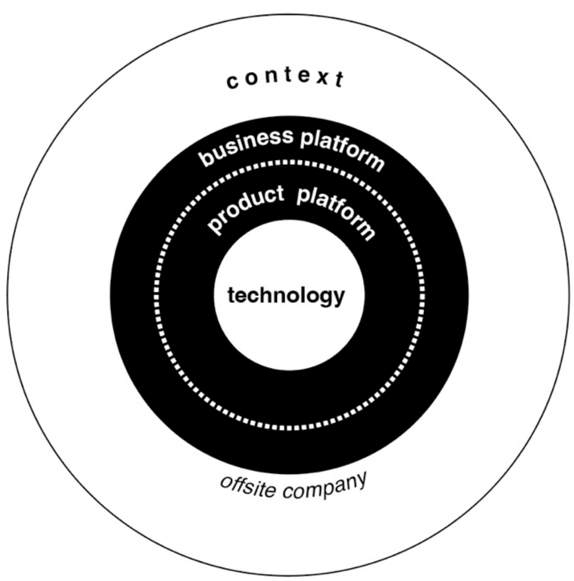
In response to this conundrum, McKinsey posits a two-pronged strategy to address the longstanding issue of stagnant and declining construction productivity. The first part of the strategy includes initiatives to "reshape regulation, rewire contracts, rethink design, improve procurement and supply chain, improve onsite execution, infuse technology and innovation and reskill workers," hypothesizing that these changes could "boost sector productivity by 50%-60%." The second part of the strategy includes a shift to "manufacturing style production systems," or *industrialized offsite construction*, that could yield as much as five-to-ten times increase in productivity.[6] Although the McKinsey report offered a more nuanced series of alternatives, many of the new players entering the offsite construction market have leaped to digitalization and robotics without adopting the other changes to process and manufacturing principles advocated in the research. This kind of technocratic

[5] Barbarosa, et al., *Reinventing Construction*, 23.
[6] Ibid., 8-9.

approach has contributed to widely publicized offsite construction failures that have reverberated throughout the US industry, further reinforcing an ingrained cultural hesitancy to evolve towards a manufacturing-oriented production process.

As an update to the McKinsey report, MOD X has developed a conceptual model that nests digitalization and technology within three other frames—the contextual frame (i.e., market, material, labor, regulations, and culture), the business platform frame (value creation, supply chain, and integration), and the product platform frame (modularization, product platforms, assemblies, and continual improvement). Allocating capital-intensive investments in digitalization and technology without first fully considering and addressing these contextual frames severely diminishes the potential of digital tools and techniques to deliver on the promise of housing affordability and accessibility. All the nested frames are key to improving the productivity of construction and the quality and affordability of housing; however, the third frame of product platforms is closest in proximity to digitalization and technology and can ensure the maximum impact of capital investment. Further, the product platforms frame is also the least understood in the US context and therefore the focus of this essay.[7]

Figure 2: Conceptual Nesting Model of an Offsite Construction Company



Credit: MOD X

[7] The conceptual diagram of the offsite construction industry is rooted in more than a decade of research and continues to evolve through MOD X advisory projects with trade associations and directly with HUD. The research origins were included in Smith and Rupnik, *5 in 5 Modular Growth Initiative*.

This paper will first define two related concepts: (1) the product platform, and (2) the process of modularization. A clearer understanding of these concepts is essential to ensuring that maximal benefit is achieved from migration to manufacturing-style production and the investment in digitalization and automation technologies. The introduction of these key principles will be supported by case studies of their implementation in offsite construction by two international companies: Sekisui Chemical in Japan and Lindbäcks Bygg AG in Sweden. Finally, these principles and subsequent case studies will be utilized to evaluate and progress the current and future development of US offsite construction of housing.

Platform Thinking: Modularization and Product Platforms

Discussions of digitalized manufacturing-style production systems evoke images of fabricating homes with the robotic arms often associated with the automotive industry. However, what truly sets apart most production industries from construction is a unified set of common concepts and practices. These approaches originated in the US during the late nineteenth century, when American industry set out to increase the efficiency of mechanized production through improved management of people, processes, and data.[8] This approach established the foundation of the "American system of manufacturing" that has evolved over time and context and permeates nearly every industry across the globe apart from construction.[9] Our research indicates that two related terms and concepts in manufacturing are most relevant and transferrable to offsite housing production and delivery: *modularization* and *product platforms*.

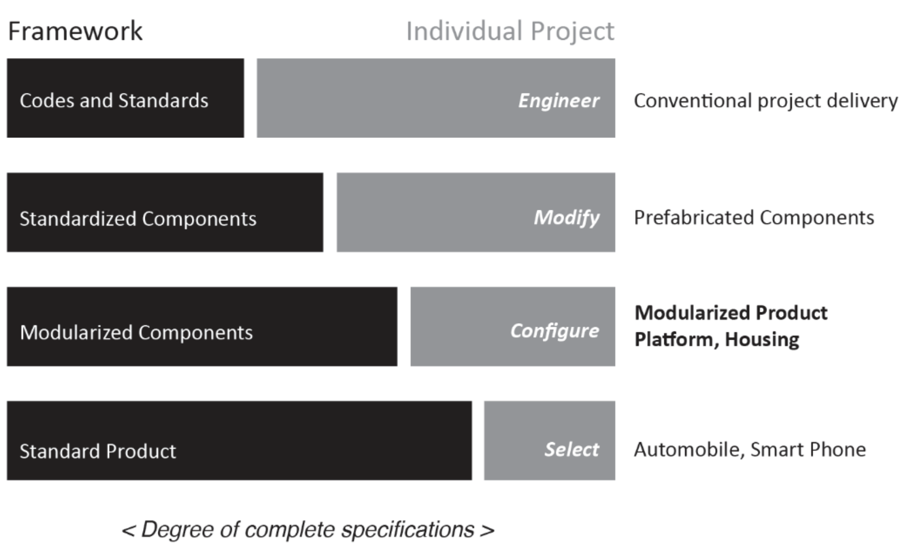
In manufacturing, there are three or more levels of production: parts as the fundamental unit, subassembly or an amalgamation of parts, and assemblies as a collection of subassemblies. Generally, the goal in manufacturing is to reduce the number of parts and the number of subassemblies that comprise an assembly to decrease unique design and handling and to increase production cycles. The end product is the good sold to the market, and the product platform is the design system or the logics of parts and subassemblies and their physical relationships. Within the offsite construction environment,

[8] Many key concepts associated with digital processes (e.g., programing) can trace their roots back to this period. For additional information refer to Rupnik, "Projecting in Space-time."

[9] One of the first studies focused on the links between industrial management and construction is Guillén, *The Taylorized Beauty of the Mechanical*. Contemporary terms like "modularization," "product platforms," and "continual improvement" are commonly used today in numerous industries with historical roots established in early twentieth-century industrial management theory. While these terms are no longer widely used in the AEC industry, they were more common during the first half of the twentieth century. For additional information, refer to Rupnik, *Projecting in Space-Time*. Due to the recent supply chain challenges facing the global economy, "platform thinking" as a business strategy has yet again become a relevant topic, as epitomized in a recent article by Deloitte titled, Exploring "Platforms": An Ecosystem Approach for Competing in a Changed World.

subassemblies are referred to as *modules,* while the terms *modular* and *volumetric modular construction* generally point to three-dimensional (3D) components of prefabrication and not necessarily modularized building components.[10] As such, product platforms are a "collection of modules … that are common to a number of products" and potentially a range of companies, and this *commonality* is "developed intentionally to achieve desired effects to create (production) value".[11] The scale of products organized as product platforms varies and can be itself subsumed within other product platforms. For example, an automobile is a product platform consisting of several subassemblies that are themselves product platforms. The automobile chassis is a platform that can be further broken down into various subassemblies. Chassis are utilized across a range of automobiles, and the respective subassemblies are in turn utilized across a range of different chassis.

Figure 3: Diagram Situating a Modularized Product Platform Approach



Data Source: Adapted version of diagram in Jensen, Lidelöw, and Olofsson, "Product Configuration in Construction."

[10] The term "volumetric modular" denotes a 3D building component, one of three broad categories of prefabricated building elements. 1D building components are referred to as "kit-of-parts" components, and 2D building components are most often referred to simply as "panels." All three types of components can serve as subassemblies or modules in a product platform. In Europe and Japan, all three types of prefabricated elements are typically organized in product platforms, while in the US, volumetric modular components are generally not organized in this manner.
[11] Harland, Uddin and Laudien, "Product Platforms as a Lever of Competitive Advantage on a Company-wide Level: A Resource Management Perspective."

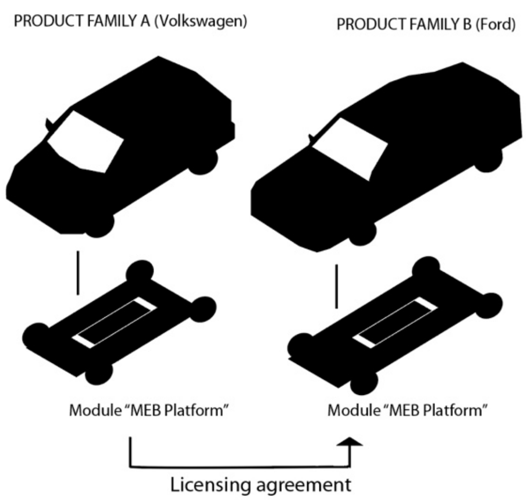
Modularization is the "activity of dividing a product of systems into modules that are interchangeable" in order to develop product platforms that are "flexible (enough) to create different requested configurations while reducing the number of unique building blocks" and allowing an assembly of those modules to achieve an "economy of scale … without standardizing the product" as a whole.[12] Variability in the end product is achieved through configuration of the platform, not the redesign of the platform in each production cycle as in construction. Modularization of products and the design and management of their modules as part of product platforms afford "continual improvement" at the scale of a factory, company, sector, and cross-sector. As the platform is employed to produce the product, buyers and users in the market provide ongoing feedback that continuously improves the platform.[13] Although there is conceptual overlap, these core concepts differ in significant ways from terminology currently used in architecture and construction. For example, *mass customization* in architecture focuses on the consumer side (or designer side) of customer-centric design but often falls short of realizing production downstream value creation (i.e., cost and time). Moreover, Design for Manufacturing and Assembly (DfMA) focuses on a bespoke project-based approach of designing with one-off (prototyping) manufacture and onsite assembly and not necessarily a modularized product platform.[14]

Serving as a contemporary example of embracing this type of manufacturing innovation, Volkswagen, the world's second largest automotive producer, is heavily investing in the future of mobility with a recently developed and transformative product platform called the Modular Electric Drive Matrix (MEB). The MEB is a modular chassis for electric vehicles (EV) across several models and brand categories.[15] Instead of redesigning the entire product, Volkswagen was able to assess its product platform, its constituent modules, and their relationships prior to identifying a particular module to redesign to include an electric battery in the car chassis. The electric battery is an entirely new module, but the remaining modules are effectively unchanged, preserving the supply chains and maintenance regimes of the components and thereby leveraging an important principle of product platform design—

[12] MODULAR Management consulting practice, typical reference indicating one of many common uses of the term "modularization" in manufacturing and services industries today.
[13] Ibid.
[14] The term "mass customization" is used in product platform theory to describe the variability that results from the establishment of a product platform. In architectural theory, the term is rarely linked with product platform theory and instead often specifically linked to the use of CAD or CAD-CAM technologies by architects to achieve a unique result, project by project. The term "DfMA" has gained wide usage in architectural theory and practice as a way of denoting the consideration of manufacturing during the design process on a project-by-project basis.
[15] Volkswagen Newsroom, "Modular electric drive matrix (MEB)."

interchangeability. Further demonstrating the potential impact and flexibility of this type of product platform concept, Volkswagen is licensing the technology to competitive automotive manufacturers, including Ford, Fisker, and various EV startups. Volkswagen can amortize the cost of the platform R&D investment, decrease barriers to EV market entry, and further accelerate electric vehicle market penetration to reduce global CO_2 emissions to support corporate sustainability objectives.[16] Managing distinct supply chains and competing in the same global markets, both Volkswagen and Ford are contributing to the continual improvement of the MEB product and process as it evolves from a tentative to an established standard.

Figure 4: Product Platform in Automobile Manufacturing



Source: MOD X

The principles of modularization and product platforms permeate all the manufacturing industries identified in the McKinsey report on construction productivity. The principles of modularization and product platforms have allowed these industries to successfully incorporate capital-intensive technologies—including mechanization, digitalization, and automation—to leverage standardization at the part level and variability at the product level.[17] In order to generate an increase in productivity and a subsequent increase in housing affordability, we posit that the same principles will

[16] Duke, "VW Group platform strategy key to e-mobility rollout"; Volkswagen AG "MEB."
[17] Factory processes are characterized as (1) manual, (2) mechanized (i.e., utilizing significant machinery), or (3) automated (i.e., utilizing significant digitalized machinery).

need to be applied for digitalization, onsite and offsite, to deliver on "the dream of the factory-made house."

The US offsite industry is currently the largest in the world measured by the number of housing units produced, with HUD Code housing constituting nearly 10% of all detached housing units delivered.[18] However, by percentage of total housing developed, the US offsite industry is well behind countries like Japan and Sweden. Further, although offsite housing in the US benefits from fabrication in a controlled environment, currently implemented widespread production methods utilize little to no digitalization or automation. Therefore, to further enable modularization and product platforms to harness mechanization, digitalization, automation, and the resulting productivity and affordability gains, along with an increase in uptake, further evolved offsite construction international markets need to be investigated. The examples of Japan and Sweden present empirically based, fully functioning models in offsite housing that provide a valuable perspective of each country's approach to increase the adoption rates of offsite construction through the prerequisite step of modularization and product platform development and resulting digitalization and automation.

Case Study 1: Sekisui Chemical | Sekisui Heim – Japan

In Japan, Sekisui Chemical's housing company—Sekisui Heim—has been utilizing modular construction methods for the past sixty-plus years. Sekisui's highly industrialized product platform based on the "unit construction method" was initially established in 1970, with a specific focus on detached dwellings and has since expanded to include multi-unit dwellings.[19] Offsite construction first appeared in Japan in the 1960s, growing steadily in market share throughout the 1970s and 1980s via a combination of efforts from the public sector, industry, and the academy.[20] The current sector is dominated by a handful of large, vertically integrated companies. Sekisui Chemical, a large plastics company founded in 1947, entered the offsite construction industry in 1960 with a prototype (Sekisui House Model 'A') that utilized

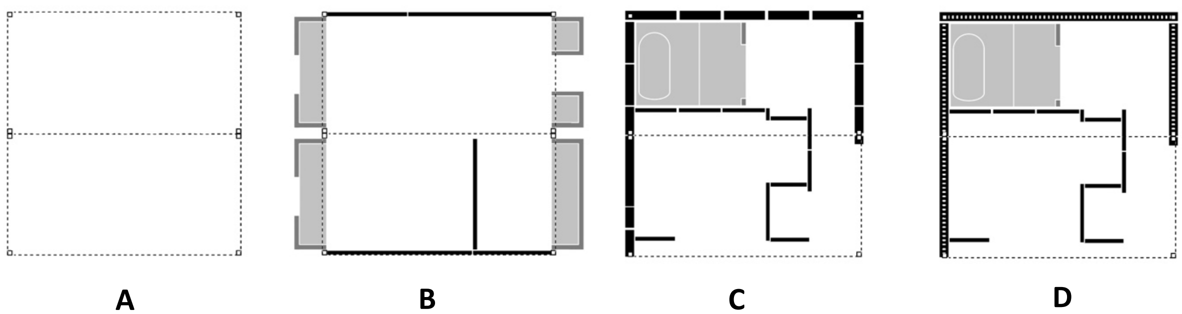
[18] Manufactured housing is the largest form of offsite construction in the US, closely followed by and related to volumetric modular construction. For more information and data on manufactured housing, refer to the Modular Housing Institute's website.

[19] MOD X's research of Sekisui Chemical has been conducted through a series of factory visits and interviews with the company and with Professor Shuichi Matsumura in 2015, 2018, and 2019. The initial findings of the research were published in Smith and Rupnik, *5 in 5 Modular Growth Initiative.*

[20] Market share of offsite construction in Japan began to increase between 1950 and 1973 through several government initiatives. Since 1973, the industry has continued to develop primarily through the efforts of individual offsite construction companies working independently or through the main trade association, the Japan Prefabricated Construction Suppliers and Manufactures Association. For a thorough history of Japanese offsite construction as it relates to mass housing, refer to Matsumura, *Open Architecture for People*.

many of its plastics products and a light-gauge steel structural frame. While the plastics proved as combustible as the wood systems they were trying to replace, the company's liquidity and manufacturing experience nonetheless combined to produce significant growth. By 1970, the original system had proven successful enough for the company to spin off a distinct housing entity, Sekisui House, while retaining significant ownership. This positive experience encouraged Sekisui Chemical to re-enter the housing market with a more highly advanced prefabricated system as Sekisui Heim.

Figure 5: Sekisui Heim's Evolving Modularized Product Platform



Source: MOD X

Sekisui Heim was created as a volumetric modular system consisting of a 3D light-gauge steel structural chassis. For the development of the product platform, Sekisui turned to Katsuhiko Ohno, a young architect whose graduate work at the University of Tokyo was focused on offsite construction. Ohno's dissertation, completed when he was developing the Sekisui Heim system, synthesized a half-century of architectural theory and manufacturing practice into the principles that continue to guide this housing system today, fifty years and 500,000+ housing units later.[21] Demonstrating a clear understanding of the principles of modularization, product platforms, and continual improvement afforded by a direct relationship to Sekisui and the Japanese automotive industry, Ohno mapped out four approaches to offsite housing delivery through the entire value chain from component manufacturing upstream to onsite assembly downstream including: (1) "structure development" described "kit-of-parts" systems, (2) "subsystems assembly" described panel systems, (3) "units-house" described volumetric or 3D components, and (4) "open system," considered an interchangeability and adaptability of components made by a variety of companies that also afforded post-occupancy

[21] For additional information related to Ohno's research, refer to Matsumura, Gondo, Sato, Morita, and Eguchi, "Technological Developments of Japanese Prefabricated Housing in an Early Stage."

transformations.[22] The first two approaches were already prevalent in Japan in 1970. The third approach described where Sekisui Heim would begin, and the open system accurately predicted where the system and the industry would arrive twenty years later, when the company embraced a circular approach to construction, offering refurbishment services to its clients and recycling up to 80% of their building components.

Ohno designed the first prototype of the Sekisui Heim system around 1970 to support the third and fourth approaches. A 3D light-gauge steel chassis, the primary subassembly or module of the system, was enclosed by a set of exterior modules, some designed as built-in storage components, while others were designed as curtain-wall-like exterior cladding. All of the steel chassis and exterior cladding modules could be manufactured by Sekisui or subcontracted to another manufacturer. For the first few years, the entire structure was licensed to a variety of manufacturers prior to Sekisui investing in the first purpose-built factory in 1974. This new approach to offsite construction failed to provide a return on investment for several years when the energy crisis of 1973 decimated many of the companies that had been supported by the Ministry "Pilot" program and forced the parent company to bankroll the fledgling unit. Nonetheless, as soon as the economy recovered, the system was ready to roll out and experienced sustained growth for several decades.[23]

In 1980, evolving consumer tastes and the importation of light-frame wood construction from the US led Sekisui Chemical to develop a wood variant of the steel system that accounts for about 20% of units sold.[24] During the 1990s, Sekisui Heim's eight factories, serving every major region of the Japanese archipelago, implemented a high degree of automation, including robotics adapted from the automotive industry.[25] Following the development of the housing system and the increased mechanization and automation of the manufacturing process, the company developed a suite of

[22] Katsuhiko Ohno's dissertation has not been translated into English. The diagram referenced was translated and published in Sato and Matsumura, "The Theory and Implementation of Components Building by Katsuhiko Ohno": 3. The article also provides an excellent overview of the dissertation.
[23] As a publicly traded company, Sekisui Chemical has provided excellent data since 2000 in English related to its business performance over the last half century. A thorough overview of the interrelationship of the parent company and the housing division is available via Sekisui Chemical Co. Ltd. Integrated Report 2020: 8.
[24] Timber-based construction dominates housing in Japan but is somewhat less prevalent in "prefabricated housing," where light gauge steel (LGS) is more dominant. In the 1970s, Japan imported American light-frame construction that is still seen as the most affordable form of construction. In the late 1970s, Sekisui Chemical recruited Katsuhiko Ohno to develop a new variant of the Sekisui Heim system using American light-frame construction. For additional information related to the history of this process, refer to Sato and Matsumura, "The Theory and Implementation of Components Building by Katsuhiko Ohno": 7.
[25] Jun and Katano, "Structuring of Sekisui Heim Automated Parts Pickup System (HAPPS) to Process Individual Floor Plans."

purpose-built proprietary digitalization solutions that includes the Heim Automated Parts Pickup System (HAPPS), designed to *pick and feed* the production line just-in-time with about 30,000 parts per house, comprising factory-produced modules or units, from a total universe of about 300,000 list parts and placed on assembly lines in order of consumption. The HAPPS program is updated monthly, incorporating new models, modifications, improvements, and calibrated against about 70,000 test floor plans prior to release, attaining a 99.5% accuracy rate. The HAPPS parts explosion process takes 1-1.5 hours from input of floor plan (graphic form), creation of system objects (abstracted floor plan information), modeled house configuration, and cross-reference to groups of parts.[26] Additional supporting information systems platforms include a sales support system (SCOPE), a process control system (SMASH), and a production system (SHIPS) that manages the manufacturing and delivery process. The development of Sekisui Heim's business platform—including its supply chain, sales network, proprietary software, and bespoke manufacturing lines—has been managed using "platform thinking" and continually improved over the last half century. For the last decade, Sekisui Heim alone held nearly 4% market share of owner-occupied housing starts in Japan.[27]

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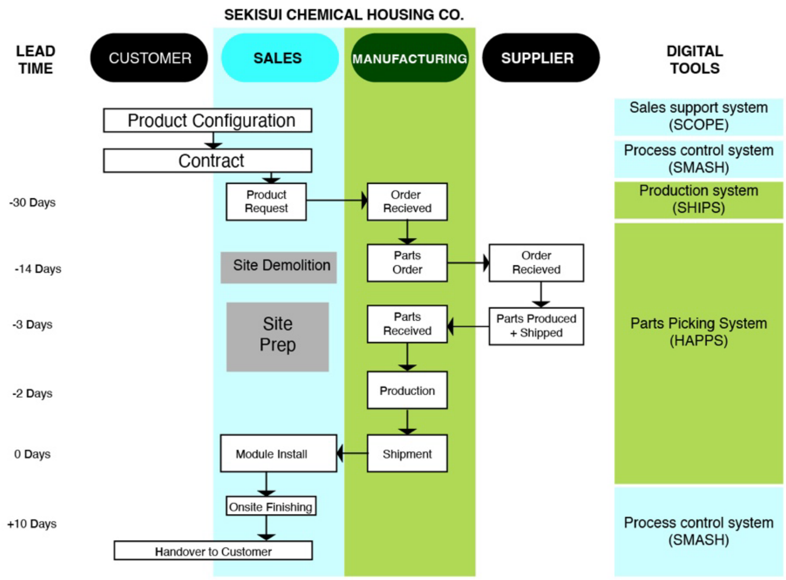
[26] Ibid.; Hall, "Tokyo Sekisui: Routinely Builds 80 Percent of a House in Three Days."

[27] In 2019, Sekisui Chemical built 10,910 homes: 85% were custom designed, owner-occupied, single-family homes on infill lots, 9% were speculative single-family homes with a majority owner-occupied, and 6% were rental multi-family. Historically, all the large offsite home builders focused on the custom-designed, owner-occupied, single-family market, but many have more recently diversified. For example, Daiwa Home now represents 10% of all rental home starts. As a result of the effective collaboration between the Building Center, Japan, the Japan Prefabricated Construction Suppliers and Manufactures Association, and the Ministry of Land, Infrastructure, Transport and Tourism, "prefabricated housing starts" have been tracked accurately for decades. In 2019, "prefabricated housing" represented 14% of all housing starts in Japan. Even site built single-family construction in Japan (70% market share) has been highly digitalized and modularized since the 1980s, with mid- to heavy-timber components arriving precut onsite for ease of assembly.

Figure 6: Time Flow Diagram of Sekisui Heim's Project Delivery

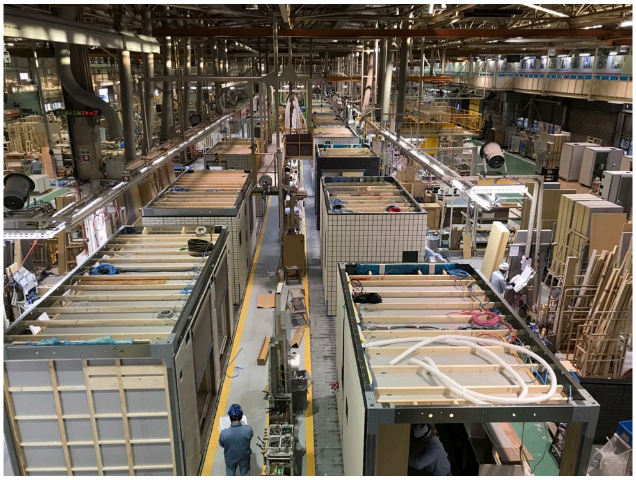


Source: Variation of a diagram by Sekisui Heim created by MOD X

The light-gauge steel chassis of the Sekisui Heim primary system has continually improved through an iterative process of delivering projects and fostering feedback loops from end customer to manufacturing. The structural components are outsourced to a steel fabricator and the 3D chassis are assembled and spot welded in a Sekisui factory by robot arms adapted from the automotive industry. The next step in the process, the application of ceramic façade panel, mirrors the development of the Volkswagen chassis previously referenced. During the mid-1970s, every Japanese offsite company had a unique approach to cladding. Around 1974, another volumetric modular company, Misawa Homes Co., developed a ceramic façade panel as a response to a competition held by the Ministry.[28] Over the next decade, several companies, including Sekisui Heim, began to integrate this new ceramic panel as a standard cladding solution into their own product platforms. Due to the size of the company and the importance of the façade component, Sekisui constructed two ceramic cladding panel factories to self-supply all its assembly factories with this critical subassembly module. The same modularization principles and digitalization tools informed Sekisui's decision to shift from fabricating its bathrooms in-house to outsourcing the fabrication of the subassemblies to a specialized bathroom pod manufacturer based on Sekisui's own specifications, thereby fostering an offsite supply chain common to manufacturing-based industries.

[28] Interview with Shuichi Matsumura, December 2018. Interviews with Mr. Utsumi, Mrs. Nagatomo and Mr. Namuar, Sekisui Chemical.

Figure 7: Final Phase of Sekisui Heim's Manufacturing Process



Source: MOD X

Modularization and digitalization have continued to increase the flexibility the Sekisui Heim system over decades of continual homeowner feedback, further increasing the company's ability to adapt to supply chain and consumer inputs the platform. Today, a highly standardized catalog of pre-engineered structural volumes supports a design and personalization process that results in no two Sekisui houses sharing a common floor plan configuration.[29] By consistently evaluating the entire process from design, manufacture, assembly, and occupancy, Sekisui has implemented several radical process improvement strategies, many of which seem idiosyncratic when viewed from the perspective of the US offsite industry. A relevant illustration relates to how the company addressed one of the major productivity impediments in the offsite industry, known simply as the "gypsum problem." Gypsum, or drywall, installed in most offsite construction systems worldwide, creates bottleneck challenges in offsite production. During manufacturing, the "wet work" and subsequent drying time of joints negatively impacts the speed of the production line throughput. Further, during transportation and particularly during assembly of modules, drywall is subject to tension forces and tends to crack, requiring additional site rework. Thanks to the use of a digitalized and modularized product platform that has fostered data collection and analysis from the design, manufacturing, and assembly of its projects since 1971, Sekisui questioned tradition and migrated the gypsum wet work to the construction site, believing the

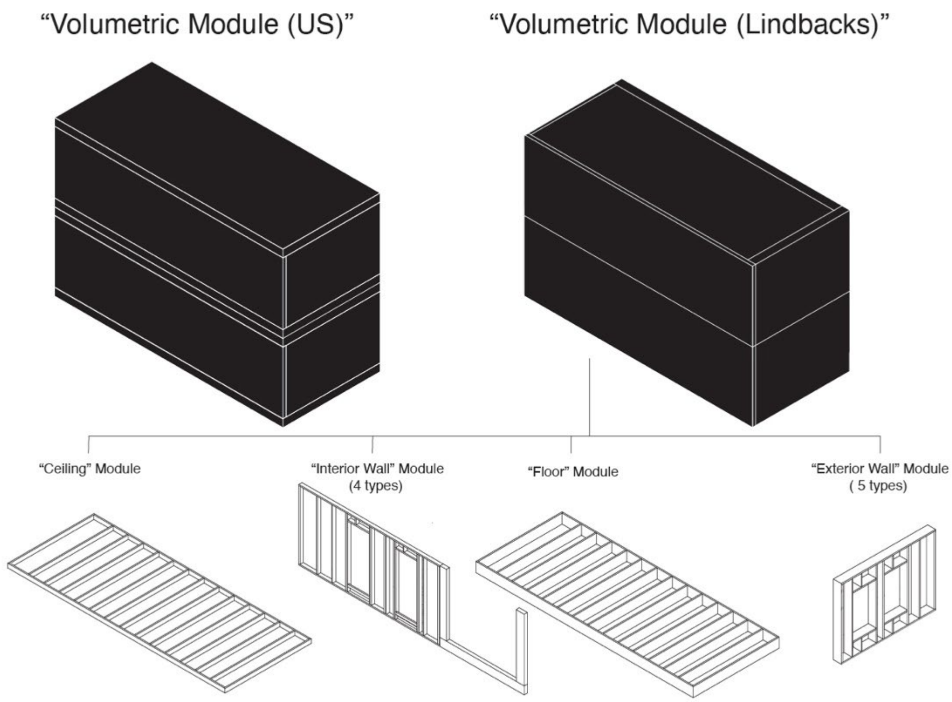
[29] The Sekisui Heim system utilizes two standard widths, two standard heights, and nine standard lengths for its volumetric module. In addition to the thirty-six (36) standard module types, there are several other pre-engineered volume types. Customers enter the personalization process through a variety of lifestyle brands, but the company does not use standard floor plan layouts.

transition would subsequently improve productivity downstream. This decision was further supported by another aspect of the company's modularized product platform, the use of a 55-centimeter dimension for the spatial planning of its walls and volumetric modules. With this dimensional standard, Sekisui can also decide on a project-by-project basis to complete walls in the factory or to ship portions of them, flat-packed in volumetric modules, to be assembled on the construction site.

This is a departure from the common ideology and practice of the US volumetric modular industry to complete as much work scope as possible offsite, resulting in large and often cumbersome 3D volumes. The results of dimensional standardization and panel/volume hybrids are performative, with Sekisui completing a single-family home in less than three months on a consistent basis. The underlying innovation is not the derived technical solution to the "gypsum problem"; rather, Sekisui's establishment of a modularized product platform that generates data for productivity analysis and improvement over time allows the company to facilitate informed and strategic process/product decisions in manufacturing. The company's capital-intensive automated digital and mechanical technology alone did not generate the solution to the wet work challenge. The solution was instead enabled by the tools supplied by an embedded culture of "platform thinking."

Case Study 2: Lindbäcks Bygg AG – Sweden

Figure 8: Volumetric Module Comparison of US vs. Sweden



Source: MOD X

Lindbäcks Bygg, originally a forestry products company, started manufacturing detached dwellings in the mid-1960s before shifting focus to mid-rise, multi-unit housing in the mid-1990s.[30] The Lindbäcks project delivery process from design to assembly clearly illustrates the relationship of modularization and digitalization in Sweden. Although Lindbäcks is uniquely focused on mid- to high-rise multi-story housing, it shares several common traits with the majority of Sweden's offsite industry. Most offsite construction in Sweden is wood-based, more specifically light-frame or "American frame" construction. However, light-wood frame in this context is digitally modeled, a practice that is growing in the US but is still quite rare.[31] With fully digitalized framing, panel manufacturers either procure precut

[30] MOD X research of Lindbäcks Bygg AG began in 2017 with a visit to the company and has included several interviews with Helena Lidelöw, the company's product platform manager and former head of research and development. For additional information on Swedish offsite construction, refer to Lidelöw, "Offsite Construction in Sweden: From Technology-driven to Integrated Process."
[31] In Europe, light-frame construction is synonymous with offsite construction. All projects are three-dimensionally modeled prior to fabrication into open or closed panel components. In the US, California-based Entekra is a good example of this process with the company importing this approach after decades of experience in Ireland. More

lumber from a supplier or utilize in-house equipment to prepare a packet of components before assembling them into panels utilizing mechanized, semi-, or fully automated panelization equipment. This, in turn, produces panels that are highly precise—increasing productivity onsite during assembly and enhancement, or offsite if they are further enhanced into closed panels. Swedish volumetric modular manufacturers, including Lindbäcks, have implemented an additional step in production by utilizing 2D closed panels to create 3D volumetric modules prior to transporting and assembling onsite. Regardless of the degree of enhancement and prefabrication, this modularized and digitalized approach provides a high degree of control and efficiency.

Figure 9: An Essential Formation Step in Lindbäck's Manufacturing Process

Source: MOD X

Most housing products manufactured by Lindbäcks are designed with developer-architect teams as the primary user group, particularly in boom cycles when the company focuses less on affordable housing and its own development projects. Developers and architects are provided an architectural manual intended to explain the Lindbäcks product platform principles and concepts sufficiently enough to prepare the equivalent of a design development set of project documentation drawings or a digital model.[32] The in-house engineering team then assumes control of the project documentation, with the developer and architect reviewing the project at key intervals. The architectural manual does not

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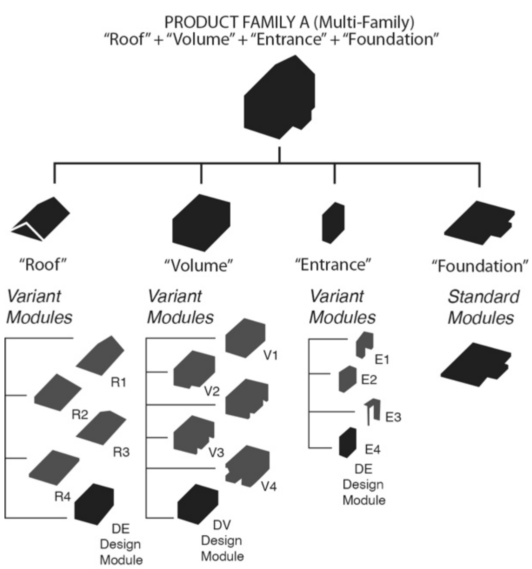
recently, Builders FirstSource, a large national building products supplier, has started offering its clients a similar service and product range.

[32] Over the last two decades, Lindbäcks has continually improved its interface with client architects by creating its first *Arkitektmanual,* or "architectural manual," in 2020. This document is intended to provide architects with basic spatial planning information to prepare schematic sets that will then be further developed into technical documentation by Lindbäck's in-house design and engineering team.

include standard volume sizes or types; it is instead built around a series of standard wall types and other parameters including largest open span between volumes. The key module or subassembly of the Lindbäcks product platform is not the volume but the wall panel and floor cassette. By modularizing the 3D volumetric system into a set of 2D elements, the company can balance the needs of a standardized manufacturing process with a flexible, customizable unit and building layout. The panel logic also allows the flexibility to ship either volumes or closed panels to the building site, with panels often being used to assemble the common spaces in multi-unit buildings. As aggregations of panels, the volumes themselves are more versatile in terms of achieving superior thermal, acoustical, and structural performance, since each edge of the volume can be calibrated to final location assembly requirements. The wall panels are further modularized into subassembly components, including the framing and insulation that are both ordered precut to specifications for efficiency of assembly. While Lindbäcks has continued to push the vertical boundaries of light-frame construction up to eight-story buildings, the modularized and digitalized system has also allowed for the seamless integration of engineered lumber—including Cross-Laminated Timber (CLT) and Glue-Laminated Timber (GLT)—without modifying the entire product platform or myriad subassemblies.

Figure 10: Lindbäck's Modularized Product Platform

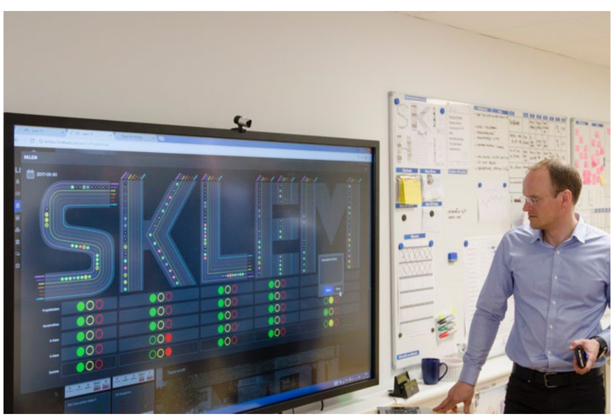


Source data: Variation of diagram utilized by Lindbäcks

If we compare Lindbäck's approach to that of the automotive industry, volumetric modules and complete buildings are significantly more customized than a typical automobile, while the wall panels, floor cassettes, and bathroom pods approach similar standardization. As Lindbäcks migrated its focus from single-family to the multi-family market during the 1990s, the same principles of continual improvement supported by a modularized product platform allowed a gradual evolution that enabled the company to adapt existing supply chain and manufacturing processes to a different scale and customer base. As a result, Lindbäcks does not inform customers that its schematic designs are not adequately “modular” nor do they inform customers that the company can “build anything”; instead, the company developed an interface that is able to balance the need for standardization and customization without productizing its buildings using repeatable pre-designed floor plan or volumetric module configurations.

Lindbäcks approached the development of its manufacturing processes with the same mindset that guided the development of its multi-unit housing. Following the example of other successful Swedish industries, Lindbäcks has nurtured a collaborative data culture in which each employee is actively involved in the assessment and improvement of daily tasks. Proprietary software clearly accelerated data gathering and management, and the company’s core social practices continued to provide a solid foundation for high levels of factory productivity. The same deliberate modularization and continual improvement of labor practices supported crucial decision-making that has supported Lindbäcks shift into multi-family volumetric modular work in the nineties continues to guide the approach behind their new factory in 2018, the largest of its kind in the European Union.

Figure 11: Lindbäck’s Proprietary Digital Manufacturing Management System



Source: MOD X

Like Sekisui, Lindbäcks has also implemented a modularized product platform approach to address the “gypsum problem” in a manner that is appropriate within the company’s context and business platform.

The company applies gypsum wall board to wall panels early in the manufacturing process, before assembly into volumes. Since the wall panel framing is fully digitalized and automated, Lindbäcks can plan and manage the application of subsequent finishes to minimize the number of seams and material waste. Since wet work is still required to finish the wall panel seams and penetrations, Lindbäcks invested in equipment to accelerate the drying of the panels prior to assembly on vertically heated racks. The decision to deploy the capital investment in the manufacturing process was made with a complete understanding of the return on that investment supported by decades of manufacturing data.

Working within different contexts and business platforms, Sekisui and Lindbäcks provide two very different solutions to the gypsum challenge. Each company's model responds to its respective cultural platform thinking and unlocks creative solutions to overcome the longstanding issue. Sekisui and Lindbäcks have both generated innovative industry-leading results. The principles behind the success of these two companies are the same as those that have served manufacturing-based production systems in other industries for much of the twentieth century. These offsite construction companies utilize modularization to rationally break down a product into a set of components and processes and then link those elements into a product platform. This organizational foundation informs each company's digitalization strategy and ultimately supports a highly automated manufacturing process. These elucidative case studies utilize means and methods from the US light-wood frame system. A closer inspection and analysis of how these mature international markets have been nurtured to ensure that offsite construction can deliver on its longstanding promise of quality, economy, and sustainability demonstrates that a similar framework is indeed possible in the US

US Offsite Housing Delivery, Modularization, and Digitalization

Sekisui Heim and Lindbäcks Bygg provide two clearly successful examples of the implementation of a modularized product platform approach to housing delivery over time. Leveraging this approach, these companies have been able to maximize the benefits of a fully industrialized construction process in the factory and on the construction site through the utilization of advanced mechanization and digitalization tools. What can the US learn from these two examples? What are the key barriers to the implementation of this approach in this context?

To answer these questions, we turn to the conceptual model introduced earlier in this text, working from the inside out starting with the light-wood frame technology. The US is fortunate in that it is unlike much of the rest of the world where mass housing tends to be built using wet, heavy construction systems relying on masonry and concrete; in the US, mass housing construction means and methods are much more similar to those of advanced offsite construction sectors. It is not a coincidence that light-frame (or American) construction was imported to parts of Europe and Japan a half-century ago, and in all those countries, offsite construction is now nearly synonymous with light construction in wood and steel. This also means that the hardware deployed in factories and the software platforms used to manage design and manufacturing are already designed around systems of construction common in the US. Therefore, access to relevant technology is not the obstacle.

As asserted through the two case studies presented, investment in the digital and mechanical technologies alone, without the implementation of platform thinking, will not result in increased housing affordability. In fact, quite the opposite is likely to occur where capital-intensive investments can increase costs compared to conventional construction, which in the US utilizes the same highly economical means and methods. Platform thinking is currently rare-to-nonexistent in the construction sector, but it is common in other parts of the US economy. The barrier to applying platform thinking to housing delivery, and not just construction, may simply require acknowledging how substandard the current situation is *and* how long this type of approach took to implement in other industries where it is now commonplace. In countries like Japan and Sweden, it should be no surprise that experts from other industries, including automotive, plastics, and forestry products, played a key role in translating these principles. However, in all these cases, the specificities of housing delivery and construction were also acknowledged, along with a realistic measure of the time it would take for the transformation to occur. The business platforms frame is closely linked to the notion of product platforms and will require a similar approach to implement interdisciplinary teams with broad knowledge of housing delivery idiosyncrasies and willingness to play the long game.

As we move to the outer ring of the conceptual mode, we arrive at what is often perceived as one of the most significant barriers to the uptake of offsite construction: existing regulatory frameworks. These frameworks are also often linked with less tangible contextual factors, like a particular culture around housing. The offsite construction industries in Japan and Sweden faced significant contextual barriers to adoption, some of which were very specific but many quite like those found in the US. In both countries, a collaboration of public agencies, industry (trade associations and leading companies), academia, and the non-governmental sector was required to overcome barriers. These changes occurred over time and concurrently with the adoption of platform thinking within the respective industries. The supportive regulatory framework changes introduced in these countries provide valuable insight and key lessons that could inform future US offsite policy strategies and programs. The Modular Building Institute (MBI) and various municipal, state, and federal agencies have been increasingly interested in these critical learnings with the development of the ICC Offsite Toolkit.[33] More recently, the US Department of Housing and Urban Development has decided to assess its past role in overcoming barriers to the growth of offsite construction as a basis for considering its future role in this industry.[34] As the US offsite construction environment continues to evolve, effective transfer of empirically supported methods, practices, policies, and programs from developed international industries will become progressively more feasible.

A unique obstacle to the growth of offsite construction, particularly when it comes to an appropriate increase in technology paired with platform thinking, may lie in current industry itself. In Japan, Sweden, and other countries where offsite construction has attained significant market share, most offsite systems are either kit of parts, one-dimensional (1D) prefabricated elements, or panelized, 2D prefabricated elements. Sekisui and Lindbäcks both utilize volumetric modular, or 3D elements, that in turn comprise subassemblies of panelized and kit of parts components. The US presents a unique offsite construction context in that it is currently dominated by 3D prefabricated systems, volumetric modular, and manufactured housing structures that are almost entirely completed in the factory before being transported to the construction site. There are numerous reasons for the market dominance of this approach; however, the clearest determining factor is the federally managed and regulated manufactured housing program, also known as the HUD Code. The HUD Code program evolved out of the federal standardization of the existing recreational vehicle (RV) industry and the regulatory byproducts of Operation Breakthrough, which unsuccessfully attempted to introduce several new offsite construction systems to the US market. In contrast to the Japanese and Swedish programs, Operation Breakthrough emphasized technology transfer over regulatory reform and failed to collaborate with the trade associations to mitigate issues between the public and private sectors. However, a Congressional assessment of the program did acknowledge that while Operation Breakthrough "did not prove the marketability of most of its sponsored housing construction methods," it did expose "builders to new construction methods and materials, exploring new methods of evaluating housing construction, encouraging changes in building code requirements, and supporting statewide building codes."[35] Those changes directly supported the establishment in 1976 of the Manufactured Home Construction and

[33] Building upon the *5 in 5 Research Roadmap* recommendations for industry standards, the Modular Building Institute (MBI) has collaborated with the International Code Council (ICC) on two new standards: (1) ICC/MBI 1200-2021 Standard for Off-Site Construction: Planning, Design, Fabrication, and (2) Assembly and ICC/MBI 1205-2021 Standard for Off-Site Construction: Inspection and Regulatory Compliance.
[34] The "Offsite Construction for Housing: Research Roadmap" is available for download via HUD's website.
[35] Staats, *Operation Breakthrough*, ii. Outlines six areas of research in order to overcome barriers to offsite construction adoption in the US.

Safety Standards (MHCSS), commonly known as the HUD Code, and the Manufactured Housing Institute, the industry's main trade association. The volumetric modular industry originated from the manufactured housing industry, utilizing similar techniques to construct 3D building sections that are assembled onsite into larger structures. Completed manufactured housing is governed by its own code, the HUD Code, and structures constructed using volumetric modules are governed by the International Residential Code (IRC) for single-family units, and the International Building Code (IBC) for multi-family. The manufacturing and assembly process of these two offsite construction systems is regulated using a common set of frameworks originally developed as part of Operation Breakthrough and subsequently tailored to the manufactured housing industry. Furthermore, both manufactured and volumetric modular housing share several similar manufacturing approaches that are difficult to automate using commercially available technology today, with manufacturers choosing to fabricate 3D structural frames before applying enhancements such as insulation. In contrast to international systems that have continually improved through a feedback process including inputs of design, manufacturing, assembly, and occupancy, US manufacturing has not changed significantly in more than fifty years.

This common history and regulatory framework explain some of the key differences between volumetric modular methods practiced internationally versus methods practiced in the US. In Japan and much of northern Europe, nearly all light-frame construction is fabricated offsite utilizing some degree of modularization, mechanization, and digitalization. The high degree of modularization and the prevalence of product platforms in volumetric systems worldwide is clearly informed by the broader context of panelized and kit-of-parts construction. Specifically, most volumetric systems are first precut as kit-of-parts components, followed by assembly into open or closed panels (components with enhanced levels of finish including insulation, drywall, windows, etc.) before assembly into volumes prepared for transport. This approach affords volumetric modular companies high-level flexibility, and what McKinsey refers to as a "hybrid approach," mixing volumetric and panelized modules in the same project.[36] In contrast, the means, methods, and regulatory framework in the US developed around the single-wide trailer is the single most typical offsite housing type. While these structures are often constructed in an assembly-line sequence, production resembles typical onsite construction in many ways, with much of the building enhancement occurring manually on a 3D frame as opposed to horizontally on a 2D panel, as is the common practice overseas. The US practice is not only less efficient with reduced ergonomics, especially when applied to multi-volume assemblies; it is also incompatible

[36] Bertram, Fuchs, Mischke, Palter, Strube, and Woetzel. *Modular Construction,* 10.

with a growing suite of mechanization and digitalization technologies that has been developed internationally since those technologies were designed around the fabrication and enhancement of 2D subcomponents that can, in turn, be assembled into 3D assemblies in the factory or on site.

At both extremes of the conceptual model—the contextual end where regulatory change and industrywide standards are currently in development, and the technology end where a growing number of international and domestically cultivated digital and mechanical tools are becoming more readily available—there is significant progress. In addition, there are increasing examples of platform thinking within the industry itself. In the single-family segment, two teams of architects working on opposite sides of the country, Resolution: 4 Architecture (RES4) in NYC and Connect Homes in Los Angeles, offer unique case studies on how this approach can be applied in the US context. NYC-based RES4 entered the volumetric modular industry through the Dwell magazine Home Design Invitational in 2003, where 16 architects competed to design a modern prefab home. RES4 submitted the only design developed around an existing manufacturing process and since that time, the company has continued to develop a "Modern Modular" set of spatial and tectonic parameters informed by the standards of various partner factories based on typical spatial metrics of housing. Although RES4 does not control the manufacturing process, it exerts effective influence by introducing continually improved standard details and assuming the role of "dealer-builder" by occupying the space between the end client, modular manufacturer, and site contractor. In 2010, Los Angeles-based Connect Homes started developing a unique approach to volumetric modular by patenting the first version of its system. In an approach reminiscent of Sekisui Heim, the Connect Homes system utilizes a standard structural steel chassis with width specifications that allow transportation without special permitting. The chassis also affords the system a high degree of tolerance, allowing Connect Homes to finish the interiors and the exterior cladding to a much higher level than a typical volumetric modular manufacturer. Like Sekisui, Connect Homes started by first leasing manufacturing space and relying on subcontractors before establishing its first purpose-built factory in 2020. This product platform approach has allowed Connect Homes to continually improve the system and support entry into a second market segment, homeless shelters, utilizing the same basic methodology.

As demand has increased for multi-family housing, the volumetric modular industry has largely shifted its focus from single-family construction. A primary obstacle to this transition has been the lack of coordination between volumetric modular manufacturers, AEC professionals, and contractors.[37] Prior

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[37] This barrier to offsite construction was identified by most AEC professionals during our survey of the industry in 2017. The results are included in Smith and Rupnik, *5 in 5 Modular Growth Initiative.*

to this transition, the volumetric modular industry followed the project delivery method established by the manufactured housing industry, with factories developing a network of dealer-builders and approved contractors that engage directly with homebuyers and are also responsible for completion of onsite scope of work. Instead of developing product platforms that balance the needs of manufacturing, assembly, market demand, and leveraging continual improvement processes, the factories have utilized "models" that standardize products and entire volumes with minor opportunities to variation and improvement. This lack of a product platform approach and a reliance on relatively inflexible models have made the shift to multi-family production challenging for the established volumetric modular industry as compared to companies like Sekisui and Lindbäcks. Without an established network of "dealer builders," multi-family volumetric modular project teams are forced to invent real time solutions one project at a time.

The complexity of multi-family projects has led some modular manufacturers to expand their engineering and drafting departments and invest in CAD and BIM software packages. With few exceptions, most companies have generally avoided significant modifications to their operations or equipment. In wood-based volumetric modular manufacturing, Boise-based AutoVol has adopted significant automated mechanization and digitalization in its production processes. Another factory, Chicago-based Z Modular, has invested in automation and digitalization in steel-based volumetric modular manufacturing inspired by the automotive industry to inform the design of production lines. In both cases, these companies have assisted their clients with a project delivery approach more akin to Design for Manufacturing and Assembly (DfMA) on a project-by-project basis, resulting in bespoke prototype manufacturing versus developing a modularized product platform.

One major initiative that focused on developing a modularized product platform for the US multi-family housing market connecting design to manufacture and assembly was attempted by the well-funded, SoftBank-backed Katerra in the form of its three-story garden apartment project.[38] Katerra relied on the same light-wood frame mechanization company, Randek, which was used by and from Sweden in the offsite construction sector. The company decided to invest in a more significant digitalization platform through its use of CATIA, a multi-platform CAD, CAM, CAE software suite originally developed by the aerospace industry. Katerra also developed a series of digital components with Autodesk Revit to communicate the design parameters of the product platform with client design

[38] The authors toured Katerra's first purpose-built factory in Phoenix in 2017 and conducted a series of interviews with Craig Curtis, the company's chief architect. Initial findings were published in Smith and Rupnik, *5 in 5 Modular Growth Initiative.*

teams. In 2017, Katerra constructed its first purpose-built factory, design, and sales center in Arizona for this product platform, followed by a second more-automated factory in California in 2020. The product platform was designed to support continual improvement with the first iteration consisting of simple framed walls, but with plans for increasingly prefabricated and enhanced wall panels and the option to replace floor cassettes (panels) with CLT panels. The company also attempted to develop this product platform to simultaneously comply with regional building codes to appease the relevant Authority Having Jurisdiction (AHJ) in several US markets.[39] Katerra filed for bankruptcy in mid-2021 due to a wide range of strategic miscalculations; however, much of the thought process and planning behind the manufacturing system was aligned with global best practices.

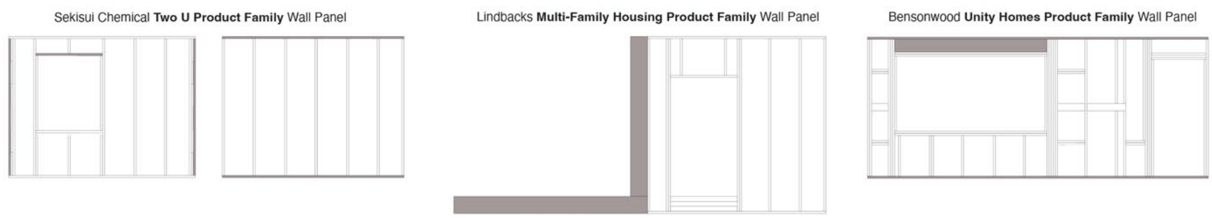
Katerra serves as a high-profile illustration of attempting hyper-accelerated growth and assuming too much scope in too little time. Conversely, New Hampshire-based Bensonwood is a clear example of gradual evolution of an offsite construction company that follows established basic principles of modularized product platforms that inform appropriate use of hardware and software.[40] Founded in 1973 out of a genuine frustration with the rapidly declining quality of housing construction in the US, Bensonwood originally focused on reviving the lost traditions of heavy timber construction. The company eventually reimagined American light-frame wood construction—albeit through the lens of the Swedish improvements realized through panelized product platforms. In 2012, Bensonwood continued to diversify the core business of high-quality heavy timber construction with the founding of Unity Homes, a closed-panel modularized product platform that serves the mid-range single-family market. When the company decided that this product platform had adequately matured, Unity Homes invested in a new facility with increased mechanization in the form of German-based Weinmann equipment and digitalization, developed using Cadwork, to communicate with that equipment. The company also engages Revit architectural design software to facilitate the design phase using dimensional standard logics. Revit solid modeling output is then converted to preestablished subassembly platforms in Cadwork that have integrated manufacturing intelligence and are continuously improved through ongoing project cycles. The Unity Homes modularized product platform serves as the key link between these two software platforms that were unified by a leading Swedish

[39] The fragmented nature of US building inspection processes dominated by a myriad of Authorities Having Jurisdiction (AHJs) is often seen as an obstacle to increased productivity in construction, not only by limiting the possibility of utilizing more standardization housing solution, but also by adding significant time to project schedules. HUD identified this issue as one of the major factors in the relative failure of Operation Breakthrough.

[40] The authors have studied Bensonwood's development over the last decade with numerous tours of company fabrication facilities and interviews with the company's founder, Tedd Benson, and other staff members.

engineering consultant, with the development of a manual project management system that progressed over time to a digital implementation.[41] To further ensure this capital investment in capacity and capability would be financially sustainable, Bensonwood developed two new business platforms based on the same closed-panel components including (1) Tektoniks, which offers closed-panel component kits to other construction professionals, and (2) Open Home, a second business platform that affords customers a higher degree of customization than the Unity line—at a higher cost—through established partnerships with a number of architects, including Kieran Timberlake and Lake Flato Architects.

Figure 12: Examples of Modularized Digital Framing



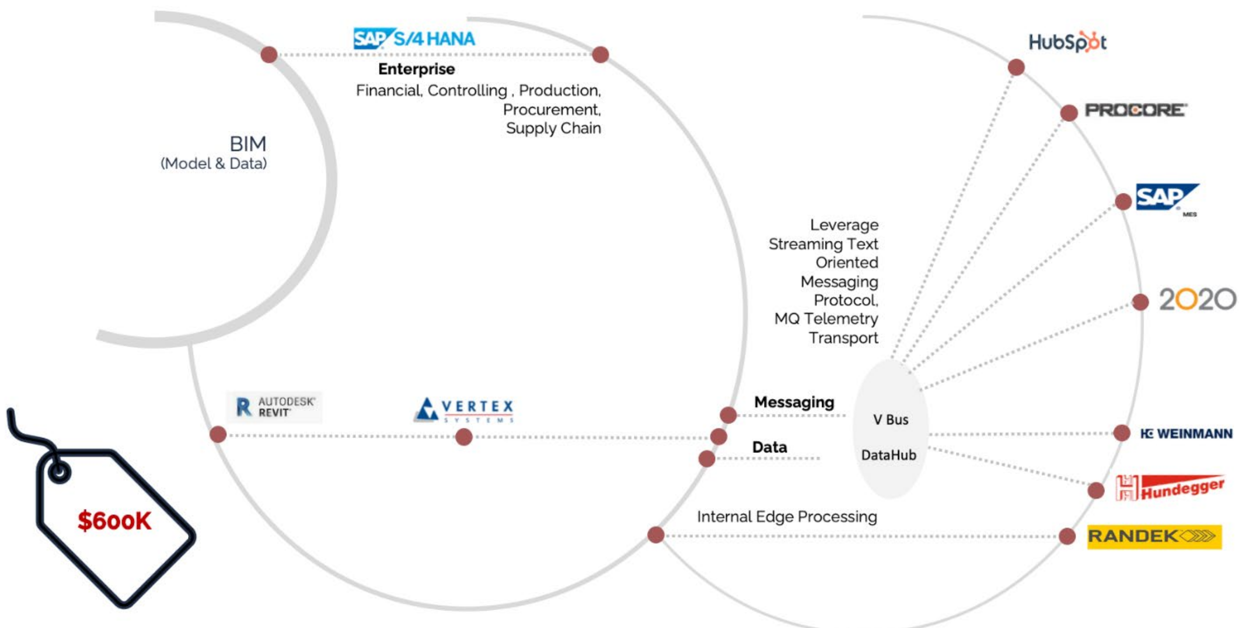
Source: MOD X

Following the historical examples set by Japan and Sweden with product platforms leading to digitalization and modularization, there are select instances emerging in the US of manufacturing-style approaches to housing. Founded in 2009, Philadelphia-based Volumetric Building Companies (VBC) started as a general contractor specializing in the assembly of volumetric modules and has gradually increased its capacity, capability, and competency over the last decade. In 2018, VBC | Manufacturing commenced operations after acquiring a shuttered volumetric modular factory in North Carolina and adapting the former single-family facility into a multi-family production line. VBC was one of the first US offsite companies to develop a "digital twin" approach by constructing a digital surrogate of its production facility as a tool to track, analyze, and plan production flow. In late 2019, Boston-based VBC | Studio was established, increasing the company's capability for translating client projects into designs to align with VBC | Manufacturing production and assembly standards. In the summer of 2021, VBC acquired the defunct Katerra's California factory, a highly automated purpose-built facility, for $21.25 million. At the start of 2022, VBC merged with Polcom Group, a Poland-based premium steel modular building and custom furniture manufacturing conglomerate focused on the hospitality market. In

[41] Tedd Benson identified the work of John Habraken, a Dutch architect who formerly taught at MIT, as key to the development of his understanding of dimensional standards. Habraken's ideas around "open building" share a number of similarities with those of Katsuhiko Ohno, the architect who designed Sekisui Heim's product platform.

addition, VBC has recruited leading international engineering expertise from Sweden to assist with ongoing strategic planning and product platform design. With this unique mix of existing US offsite construction knowledge and international capacity and perspective, VBC is poised to synthesize many of the global best practices from Sweden and Japan.

Figure 13: Volumetric Building Companies (VBC) Digital Platform



Data source: Volumetric Building Company (VBC)

Conclusion

The dream of the factory-made house is not a new aspiration. It has been envisioned for the better part of the last century in the US and around the world. At the root of this dream was the hypothesis that housing delivery would develop along similar lines to other core sectors of the economy, gradually increasing in industrialization and thereby lowering cost while maintaining or increasing quality. To some extent, this was the case for the first half of the twentieth century, but around 1970, construction diverted from other industries and began a process of deindustrialization that has continued to the present day. Despite an increasing array of digital and mechanical tools available to the US construction industry, productivity has continued to decline. Furthermore, when new technologies have been applied to construction, the results generally have not been positive. This paper asserts that it is not enough to simply apply technological solutions to housing delivery; instead, it is critical to apply the same type of platform thinking that has allowed other industries to increase in productivity and support the innovators in those industries to develop appropriate business platforms that respond to specific market conditions. We have outlined the basic concept of a modularized product platform and demonstrated the application of these concepts in two international case studies: Sekisui Heim in Japan, and Lindbäcks Bygg in Sweden. We have also shown that this approach is already being applied with success by innovative companies in the US to some degree, but that most of offsite housing delivery has not moved in this direction.

How can we accelerate the adoption of platform thinking in housing delivery to markedly increase the quality and access to housing affordably? Recent history has demonstrated that the first step in achieving the promise of offsite construction to deliver quality and affordability to the housing industry requires understanding and addressing barriers to the adoption of this mode of project delivery within a given context. This critical step is all too frequently conflated with costly publicly funded programs. In practice, however, smart investments that unify public and private sectors, trade associations, and academia around identifying existing barriers and knowledge gaps have consistently provided successful results, often through accompanying pilot programs. In Japan, the catalyst for change was seeded by the Ministry of Construction certifying factories instead of permitting projects among other efforts. In Sweden, modifications in the building code to permit taller wooden buildings set the stage for offsite housing companies to innovate. In the US, there is growing consensus around the need for similar industry transformations. MOD X has been fortunate to chair a team of industry experts in assisting the US Department of Housing and Urban Development (HUD) to identify research priorities to help foster the growth of offsite construction as it relates to housing delivery across the nation. MOD X is also working directly with HUD to assess the public sector's role in this endeavor through a comparative study of offsite construction programs in the US, the UK, Sweden, and Japan.

The regulatory framework for offsite construction is in the process of being transformed, and the transformation of contracts, standards, and financing will eventually follow. In other words, the outer frame (market context) of the presented conceptual model is in the process of improving, while, at the same time, the inner technology frame continues to evolve daily, with new technologies emerging and previously novel technologies becoming increasingly viable commercially. The development of the middle frame will fall on those currently working in housing delivery and those interested in entering the industry. For both of those groups, it is imperative to study and incorporate platform thinking that is nested in a business logic that, in turn, responds to market conditions. This paper has demonstrated how platform thinking and practices will ensure that capital-intensive investments in digital and mechanical technologies will offer a positive return on their investments. It will be equally important to develop platform thinking to assist in the transformation of the regulatory framework, standards, contracts, and financing.

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