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The Essence of Panelized Construction

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Preface

This report is the fourth installment of a series of reports that describe construction systems that can be utilized for the construction of single-family residences. The first study discusses popular traditional light-framing methods, whereas the next two reports present alternative construction systems. The initial report describes, in detail, the design process for using a light-framed wooden structural system. This report was subsequently published as a book chapter. The second report describes the design process associated with using a cross-laminated timber (CLT) structural system as an alternative to a traditional light-framed wooden system. In the second report, the same home designed in the first report was redesigned using the CLT structural system. This second report was also subsequently published as a book chapter. The third report describes the design of the same home referred to in the first two reports; however, instead of light-framing or CLT panels, cold-formed steel (CFS) is considered for the design.

This current report focuses on the introduction of prefabricated panelized construction as an alternative to site-built counterparts. The format is somewhat different than the first three; however, important information is presented for those who are considering introducing panelized elements or any other prefabricated elements, for that matter, into their construction process. Whereas the first three reports focused primarily on design-related topics, this report introduces terminology and defines panelized construction as it relates to its parent fields of prefabrication, preassembly, modularization, and off-site fabrication (PPMOF) and industrialized construction. In this report, the panelized system is defined, on-site and off-site construction methodologies are compared, industrialized construction philosophies and tools are introduced, descriptions of 7 panelized systems are presented, and lastly, an ensuing discussion is presented regarding the industrialized construction tools that are utilized by these 7 systems.

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Introduction

Interest in utilizing prefabrication, preassembly, modularization, and off-site fabrication (PPMOF) in the residential construction industry continues to grow, with rising concerns regarding housing affordability, home ownership (Smith et al. 2023), and environmental sustainability (Mitchell 2021). Greater use of PPMOF techniques and processes have been identified as opportunities for breakthrough improvements in advancing construction efficiency, quality, timeliness, cost-effectiveness, and sustainability of projects (National Research Council 2009). The National Research Council (NRC) also suggests that improvements in these aspects of construction could ultimately improve *construction productivity,* which directly affects prices for homes and consumer goods in the National economy.

The "Great Recession of 2007-2009" generated a renewed interest in improving housing affordability. The economic recession began shortly after an expansion of the housing market between 1990 and 2006 (Weinberg n.d.). According to the Federal Reserve, average home prices more than doubled during this period. A wave of research and new ideas in the field of PPMOF was initiated in the wake of the "Great Recession." In the last two decades, organizations such as the U.S. Department of Housing (HUD), the National Research Council (NRC), and the Modular Building Institute (MBI) have produced baseline studies that helped to bring awareness to the construction industry and has spurred a generation of research, methodologies and product development by both private organizations and academic institutions.

The study and implementation of PPMOF techniques and industrialized construction are continually evolving and improving as the industry receives feedback from completed construction projects and new research is introduced. Evaluation of successes and failures in projects leads to greater levels of understanding on how to effectively implement PPMOF activities in a project. Feedback and research also enable users to understand which construction activities are best conducted off-site and which are most efficiently conducted at the project site.

This report discusses the use of several types of panelized construction in the residential construction sector. The purpose of this report is to:

- Define panelized construction and discuss how it fits into the overarching principles of industrialized construction.

- Summarize knowledge in the field regarding panelized construction and present the potential user with information describing how panelized construction ties into overarching PPMOF strategies.

- Present information discussing how the implementation of panelized construction can help to improve efficiency, if utilized for the right application and implemented properly.

- Present examples and short descriptions of panelized construction systems. Discuss each system and rate how it incorporates *industrialized construction* principles.

It should be noted that this study is based on existing information in the field of PPMOF, which was obtained through a literature review. No new (unpublished) knowledge was developed for the purposes of this effort.

Important Terminology

As the offsite construction industry evolves, so does the terminology used within the industry. Terminology definitions can differ depending on the perspective. For instance, a regulating body may interpret the definition of the term "Off-site Construction" to mean something different than, say, a product manufacturer. For the purposes of this report the terminology will be taken from a manufacturing perspective. The following definitions will be utilized:

- **Industrialized Construction** (Smith et al. 2023): Uses *industrial/manufacturing-based principles* and production methods such as *advancements in computing*, *automation*, *construction planning/management* and *material science* for greater productivity. The principles can be applied to both off-site and on-site construction.

- **Off-site Construction** (Smith et al. 2023): Industrialized construction approach that leverages the factory environment to create value added subassemblies of various degrees of prefabrication ranging from 1D (Kit-of-Parts) to 2D (Panelized) to 3D (Volumetric) to complete structures.

- **Construction Productivity** (National Research Council 2009): How well, how quickly, and at what cost buildings and infrastructure can be constructed. Productivity is challenging to measure and define. Construction projects vary, and it is difficult to compare them or measure their output. The individual project characteristics--such as size, region, climate, etc.--vary. Additionally, both construction and labor productivity vary based on the resources, (materials, information, tools, equipment, workforce skills, and support services) quality of on-site supervision, project management, work-flow sequencing, weather, and safety. The NRC committee who conducted the sited study (study pertains to the capital facilities sector) believes that improvements in *efficiency* may improve overall construction productivity and help individual firms produce more environmentally sustainable projects and become more competitive.

- **Efficiency Improvements** (National Research Council 2009): Ways to cut waste in time, costs, materials, energy, skills, and labor.

- **Modularization** (Smith et al. 2023): An approach to offsite construction that uses Design for Manufacture and Assembly (DfMA) and predefined *Product Platforms* to allow for project reconfigurability and adaptability through a set of standards, and for interchangeable and continually improvable subassembly elements (2D or 3D). 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 (Rupnik, Smith, and Schmetterer 2022).

- **Modular Product Platforms** (Shuh et al. 2017): Defined by a set of modules, which can either be assemblies or components. Based on standardized interfaces, these modules can be combined diversely in order to derive a certain range of product variants.

- **Design for Manufacture and Assembly (DfMA)** (Roxas et al. 2023)**:** DfMA is a process, an evaluation method, or a technology. The method has been widely utilized since the 1980s to simplify product design and reduce manufacturing time and cost. The method involves a collaborative decision-making process wherein all implementation-related activities are considered to simplify the product system and reduce possible expenses. DfMA can be subdivided into two methods: design for manufacturing (DfM) and design for assembly (DfA). These methods focus on producing easy-to-assemble and cost-effective products without sacrificing output quality.

- **Digital Fabrication** (Ng and Hall 2019)**:** Digital fabrication is a data driven production of components, and it includes the fields of robotics, drone-based technologies, rapid prototyping, and additive manufacturing. It is developed from Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) technologies. Parametric modeling tools such as CATIA streamline data exchange to manufacturing tools such as Computer Numerical Control (CNC), enabling the industry to accurately control production from digital models with digital-based interfaces between planning, engineering, and production.

- **Lean Construction or Lean Project Delivery** (Bhawani et al. 2021): Lean Construction is defined as a respect and relationship-oriented holistic project design and delivery process with the overarching aim of maximizing value for all stakeholders. It emphasizes and realizes the customer's voice through systematic, synergistic, and continuous improvement in all aspects such as contractual arrangements, design development, construction process design, methods selection, supply chain, workflow reliability on the jobsite, post-construction operations, and maintenance.

- **Mass Customization (MC)** (Hentschke et al. 2019): Defined as an organizational strategy that aims to offer products that fulfill *customers' requirements*, potentially adding value, through flexible process and structure, with costs and delivery time similar to mass production.

- **Unitized Building Enclosure System** (Hopps and Burhoe 2022)**:** A building enclosure system generally composed of prefabricated portions or panels of exterior wall assemblies, with each panel including some or all of the primary elements of the exterior wall: exterior cladding and attachments, fenestration, air/water/vapor and thermal control layers, and structural framing.

Panelized Construction

The meaning of panelized construction can differ among users. Generally, it refers to the use of two-dimensional, plate-like, prefabricated components or assemblies that are utilized to construct wall, roof, and floor assemblies for use in a building. The panels are generally constructed off-site and erected on-site by the manufacturers' or general contractors' agent. In the new standard for off-site construction, ICC defines a panelized system as wall or floor components, which are constructed at a location other than the building site in a manner that prevents the construction from being inspected at the building site without disassembly, damage, or destruction thereof (ICC/MBI 2021). Derananian and Donlon define panelized wall systems as prefabricated panels, complete with exterior cladding, anchor systems, water/air/vapor barrier, insulation, and structural framing (DerAnanian and Donlon 2019). In the most basic application of the term, panelized construction essentially refers to a two-dimensional subassembly used for the construction of a larger assembly (e.g., Figure 1).

Figure 1. Contractors assembling structurally insulated wall panels. (This Photo by an unknown author is licensed under CC BY-SA.)

Panelized subassemblies can be subcategorized within one of the 4 commonly used categories of manufacturing units (Smith et al. 2023). When discussing the prefabrication or the manufacturing of building related subassemblies, 4 distinct degrees of fabrication are typically referred to. The first and least finished unit would be a 1D unit, where the factory would deliver a Kit-of-Parts to the customer to be assembled on-site. An example is represented in Figure 2a where the individual framing components--such as the studs, fasteners and sheathing--are provided to a contractor for assembly into a wall at the project location. The next higher level of prefabrication would involve factory assembly of 1D units into 2D units and delivery of the 2D panels to the customer for assembly at the project site. Figure 2b shows a panel completed in the factory for delivery to the project location. An even higher degree of prefabrication is achieved when the manufacturer assembles 1D and/or 2D units in the factory to form a 3D subassembly, such as the one shown in Figure 2c, called a module, or commonly referred to as a volumetric module. These modules are delivered to the customer for assembly of a larger structure on-site. Project requirements may demand a hybridized approach, such as shown in Figure 2d, where both 2D subassemblies and 3D subassemblies are produced at the factory and shipped to the project location for assembly by onsite contractors. The highest degree of prefabrication is when 100-percent of the construction is accomplished in the factory and the end-product, such as the example shown in Figure 2e, is delivered fully finished to the customer. An example of this would be a manufactured home.

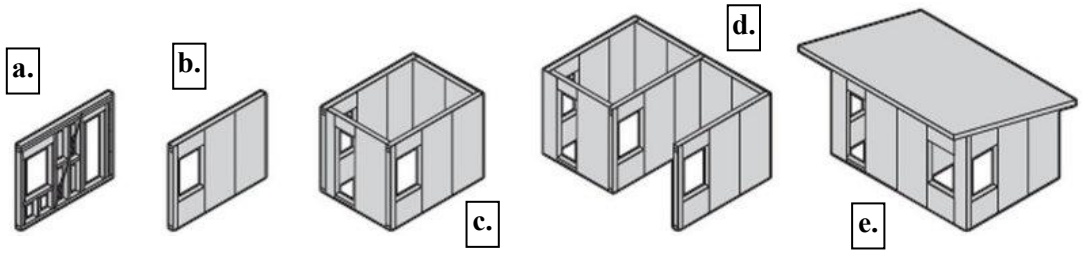

Figure 2. Degrees of prefabrication (Moradibistouni and Gjerde 2017).

Most forms of panelized construction systems can be categorized as unitized construction systems. Merriam Webster defines "unitize" as "to form or convert into a unit." When considering common panelized construction systems, the wall, roof, or floor assemblies are unitized into individual two-dimensional panels having joints with adjoining panels on two or more sides. The level of prefabrication varies for different types of panel systems. Building enclosure systems are often unitized and prefabricated to expedite construction or for quality control (QC) (Hopps and Burhoe 2022). The level of prefabrication varies with unitized building enclosure systems, as suggested in the definition. Offerings range from simple curtain wall façade systems that simply include the glazing/panel infill and framing required to support those elements, such as the one shown in Figure 3, to complete light-framed wall systems, such as the one shown in Figure 4, which include many of the enclosure components along with the load bearing framing system.

Figure 3. Curtain wall panel being installed on concrete framing (image from https://www.mornglass.com/unitised-curtain-wall-introduction-installation.html).

Unitized building enclosure systems are not suitable for all projects. These systems tend to benefit a project if stockpile space or access is limited, the construction schedule requires acceleration, redundant panels can be utilized, or when it is economical to fabricate and transport the panels to the site (Hopps and Burhoe 2022). Disadvantages of unitized building enclosure systems typically include longer design and preconstruction phases, higher upfront costs, and complicated design and construction coordination. Unitized systems can also be difficult to apply to unique building structures having unique, non-redundant panel configurations.

Figure 4. Mostly complete ACQbuilt wall panel being assembled onsite (image from https://vividribbon.ca/acqbuilt/acqbuilt-6901/).

Proper design of the complete unitized building enclosure system is critical to the successful performance of the system. Joints, in particular, can be a challenge to design in unitized systems. Figure 5 shows an example of the many components that can be required in unitized systems. There could be up to two vertical and two horizontal joints associated with each panel, depending on the position of the panel in the system. Structural stability and aesthetic appeal must be maintained across each of these joints. Additionally, the continuity of the thermal, weather resistive, vapor control, and air control layers must also be maintained according to the design and building code requirements. Consideration must also be given to the long-term maintenance requirements of the joints. In taller urban buildings, it can be especially costly and difficult to access joints for maintenance purposes. Neglect of joint maintenance can lead to system failure and costly remediation requirements.

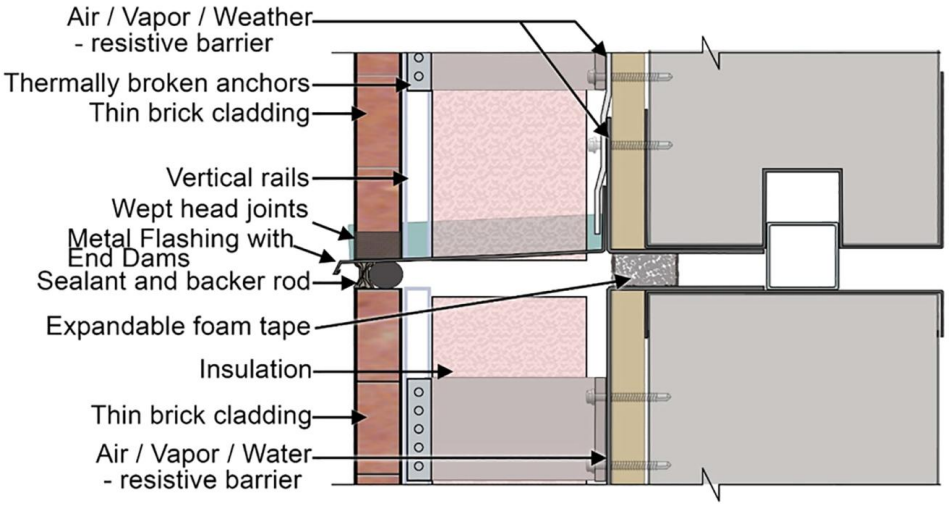

Figure 5. Unitized panel assembly with pre-compressed foam joint (Hopps and Burhoe 2022)**.**

Another consideration with respect to unitized building enclosure systems is the integration of the panels with other enclosure elements such as the structural system, roof, foundation, and contiguous cladding systems. Much of the coordination for these interactions must occur on the front-end of the design. The responsible party for joint design at these interaction points must be clear and established in advance. The joints at these locations are often complicated, such as the foundation joint shown in Figure 6. Once the panels are fabricated, there is little opportunity for field adjustments (Hopps and Burhoe 2022). It is also typical to coordinate the placement of mechanical, electrical, and plumbing (MEP) penetrations through the panels in advance.

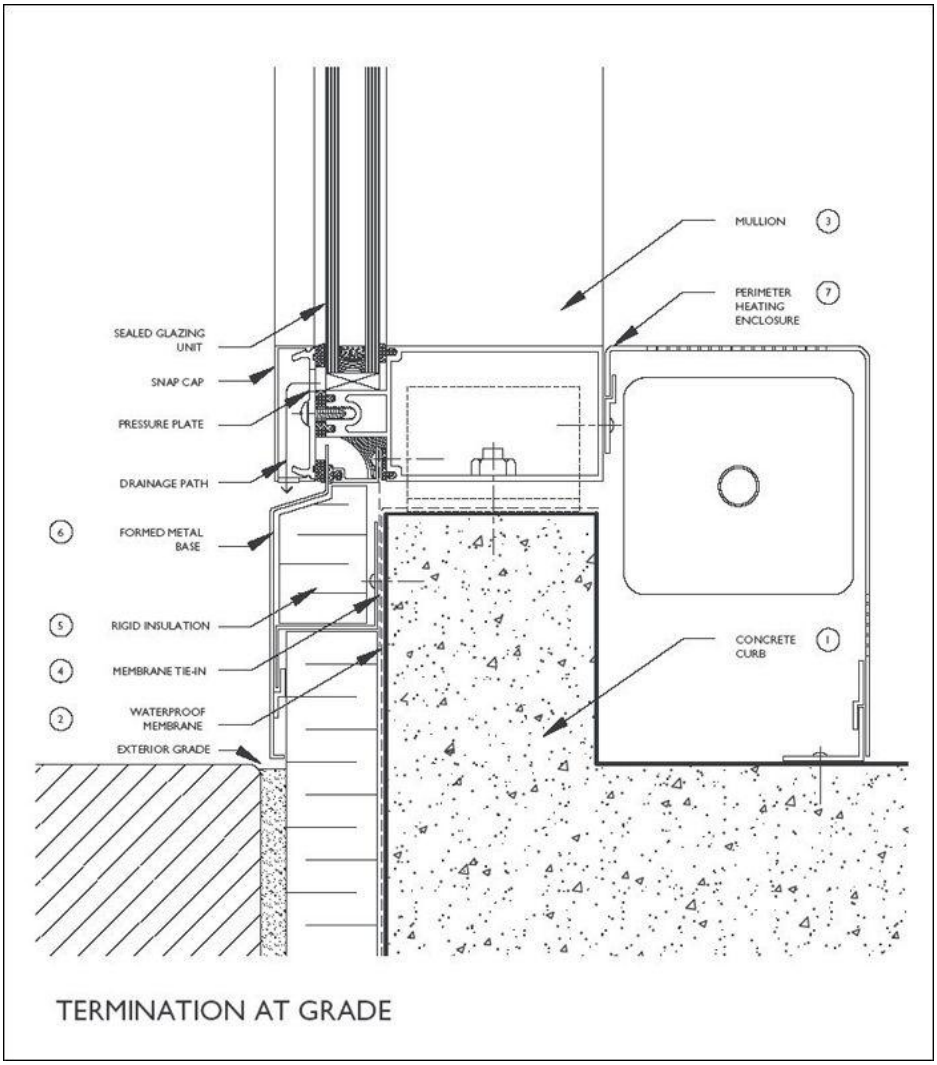

Figure 6. An example of a curtain wall termination joint at the foundation level (image from https://www.pinterest.com/pin/512143788859145080/).

When discussing the delivery of 2D light-framed panels or panelized systems, it is important to distinguish whether the panels are intended to be delivered to the project site for installation in an open or closed state. Essentially, from a building code compliance inspection perspective, it is necessary to understand whether all the panel components within the subassembly will be visible and inspectable at the project site, or will require the inspection to be conducted at the manufacturing facility. By definition, ICC assumes panels within a panelized system to be closed. The panels can also be designed and manufactured as "open panels," which are defined in the ICC standard as a modular building, modular component, or panelized system manufactured in such a manner that all portions can be readily inspected at the building site without the disassembly, damage, or destruction thereof (ICC/MBI 2021).

A study by Mitchell (2021) describes the Canadian open panel sector generally being comprised of low-tech operations, categorized by single trade functions utilizing traditional carpenters constructing panels on framing tables within warehouses, and flat-packing orders to send to construction sites where they are erected. The study goes on to say that despite the low-tech nature, this method of prefabrication leads to better quality framing in comparison to on-site framing and typically leads to approximately 30-percent time savings in framing effort. Examples of open panels would be wall, roof or floor framing flat-packs. In the study, wood light framing is primarily referred to, but it is important to note that panels can be constructed from other materials as well, such as cold-formed steel, structural steel, synthetic, and composite materials.

As with open panels, the Mitchell (2021) study describes closed panels in terms relative to light-frame wood construction. The author divides closed panels into two sub-categories:

1. One Side Closed (Level 2A): Comprised of wood light-framing, sheathing, exterior cladding, and insulation.

2. Both Sides Closed (Level 2B): Comprised of wood light-framing, sheathing, exterior cladding, insulation, windows, electrical or conduit, plumbing, heating components, and interior finish.

Mitchell (2021) claims that in the UK, the shift in acceptance to modern methods of construction (MMC) has resulted in wood open panels being replaced by closed panels. The study implies that improvements in quality control, the implementation of complex details, and the implementation of energy performance enhancements are more easily accomplished in the factory environment.

The Mitchell (2021) study breaks structural insulated panel (SIP) systems out into their own category and defines them as panels having, “two layers of sheathing (typically OSB) glued between an insulating foam core.” The Structural Insulated Panel Association (SIPA) and the American Paper Association (APA) describe SIPs as highly insulated structural building panels used in exterior walls, roofs, and floors for residential and light commercial construction. The panels are made by sandwiching a core of rigid foam insulation between two skins of structural sheathing (usually OSB). The foam core is typically composed of expanded polystyrene (EPS), polyurethane, extruded polystyrene (XPS), graphite enhanced polystyrene, or polyisocyanurate. Figure 7 shows examples of some of the foam core options. Structural adhesives are used to adhere the foam to the OSB skins (SIPA 2018). As implied in the name, SIPs are designed to be load bearing elements. Individual product manufacturers publish construction manuals and load design charts that can be accessed to understand structural capacities of their panels (SIPA 2020). Panel spans along with axial, transverse and shear capacities are examples of design values typically provided by manufacturers. APA publishes panel design values to help engineers specify panels during preliminary design.

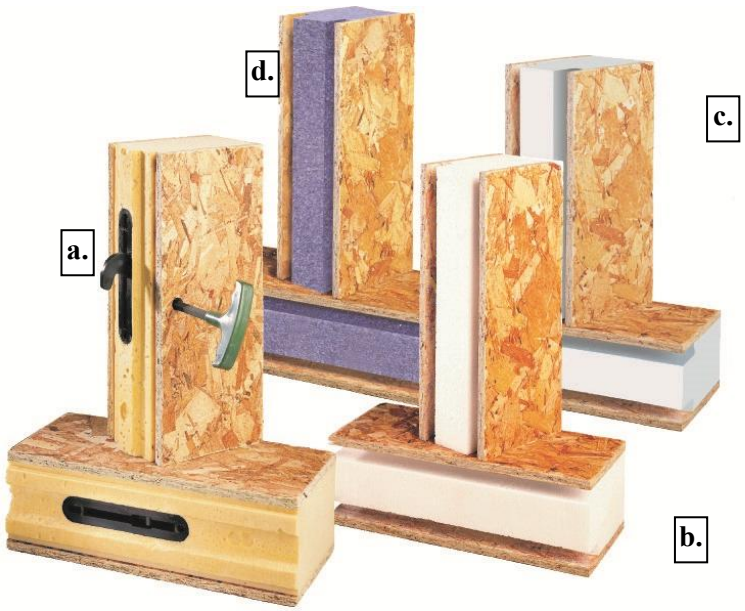

Figure 7. SIP panel foam core options: a.) polyurethane, b.) EPS, c.) XPS, d.) graphite enhanced polystyrene (image from https://www.coloradotimberframe.com/products/sip-panels/).

More generally speaking, SIPs can be categorized as a type of sandwich panel that is a broad category, which encompasses almost endless amounts of combinations of skin and insulating infill material. Sandwich panels, other than SIPs, are used primarily on commercial buildings functioning as a unitized insulative cladding system. Most sandwich-style panels; however, are not designed to resist axial and shear forces.

Building Codes and Design Basis Relevant to Panelized Construction

In most instances, panelized building products are manufactured offsite in order to improve aspects of the system, such as economy, quality, safety, and labor costs. Buildings constructed using panels and offsite construction must comply with the same building code requirements as those constructed using site-built methods; however, the inspection of panel components does not always occur in the field as with on-site assemblies.

As mentioned previously, panels can be delivered to the construction site with one side closed (open construction) or both sides closed (closed construction). Open construction panels can typically be inspected by the local authority having jurisdiction (AHJ). They can also be evaluated by an evaluation service to prove compliance if the panels are relatively uniform in design (ICC 2022).

For some closed panel systems, such as SIPs where panels are uniform and consistent, a factory evaluation approach could be employed. The 2021 IRC includes a

path for SIP compliance in section R610 (International Code Council, Inc. 2021). SIPs must comply with the requirements of ANSI/APA PRS 610.1 (American National Standard 2023). They must show compliance by bearing a grade mark or certificate of inspection issued by an approved agency in accordance with the standard.

Closed panel systems not addressed under an evaluation process may be subject to requirements under a state industrialized building code, which vary from state-to-state. Thirty-five states have established programs that govern offsite construction aspects of a project. Most state programs approve manufacturers and require a quality assurance program. Out-of-state projects are required to comply with the requirements of the state in which the project is located (ICC 2022). ICC/MBI 1200 and ICC/MBI 1205 were released in an effort to bring uniformity to the off-site construction requirements from state-to-state.

For example, Pennsylvania categorizes residential closed panels as "Housing Components," which are regulated under Section 145.34 of Pennsylvania Code Chapter 145 Industrialized Housing and Components. Chapter 145 provides a path to certification for industrialized housing, housing components, industrialized buildings, or building components. The section requires that certification shall be evidenced by an insignia of certification. Certification is the proof that the industrialized component complies with the requirements of the local building codes. A housing component shall be considered certified if the building system documentation and compliance assurance program relating to its design, manufacture, transportation, and installation have been approved by an evaluation agency under contractual agreement with the PA Department of Community & Economic Development (DCED). Additionally, the housing component must be manufactured under the approved building system documentation, inspected, and approved by an inspection agency (under contract with DCED).

Brief Comparison of On-Site Versus Off-Site Construction

As discussed previously, the utilization of off-site construction methods is not appropriate for all projects and all activities related to a specific project. On-site construction methods may be more appropriate for all or a portion of the project depending on the schedule, design, materials, geometry, etc.

The utilization of off-site construction methods can benefit certain projects if used appropriately. The Modular Building Institute (MBI) claims in a recent report (MBI 2023) that the key advantages of modular construction (one form of off-site construction method) include cost certainty, schedule certainty, product quality control, reduced environmental impact, and improved worker safety. It is important to recognize that in the same report, they also provide a reference to design considerations and best practices for Architects. Failure to adhere to manufacturers' recommendations can often marginalize the benefits of off-site construction.

One industrial EPC (Engineering, Procurement, and Construction) firm suggests that the benefits of off-site construction include reduced project duration, mitigation of safety risks, reduced overall risks, improved quality, and waste minimization. They list the cons of offsite construction methods as site constraints,

increased engineering, planning, and coordination requirements, decreased flexibility, and potential higher costs. They also suggest that offsite construction methods are best suited for projects that are schedule-driven, remote, or have labor or weather constraints, or for project sites with a lack of local infrastructure, and project sites with access for delivering large, prefabricated assemblies (H+M Industrial EPC 2021). Literature also suggests that off-site construction can improve certain sustainability-related (Moradibistouni et al. 2019) and life-cycle-related (Kamali et al. 2019) aspects of some construction projects. Off-site construction can also be leveraged to implement difficult detailing associated with modern energy codes and durability requirements.

Figure 8. An example of a repetitious building form suitable for modular construction methods (MBI 2023)**.**

The whole building design guide (WBDG) offers several suggestions regarding when off-site construction should be utilized (Smith 2016). They suggest that projects, such as the one shown in Figure 8, restricted by schedule, such as schools and dormitories, repetitious projects such as classrooms, office units, dwelling units, and bathroom pods may be appropriate for off-site construction methods. They also warn that the project delivery method can have an impact on the decision to use offsite construction. Additionally, factors such as the level of off-site construction experience of the team as well as their history of working together in the past can also impact the decision to use offsite construction. The WBDG lists several instances where it is less likely that off-site construction will be deployed. These include sites that are accessible and affordable with a long construction season; the WBDG points out that these sites are less likely to benefit from off-site construction. Also included in the list are sites with access to a wide range of affordable materials, sites that have limited local manufacturer resources, and sites that have access to affordable labor. Lastly, included are sites with off-site construction regulatory constraints.

Construction activities that do not occur off-site must occur on-site. The decision of whether to complete activities on-site or off-site is largely based on the

context and needs of the project served by the manufacturing facility and/or the facilities business platform. Activities that are generally accomplished more efficiently on-site, such as the construction of panels into larger assemblies and customized components like foundations and footings, are generally performed by the on-site construction contractor. Shipping economy and regional transportation regulations can influence the offered manufacturing unit, as can the state industrialized housing inspection requirements and the regional onsite contractor capabilities.

There are a variety of reasons why some activities are more efficiently or economically completed on-site. For example, low-rise residential structures are typically constructed onsite using light-framed wood construction. This system of construction is generally preferred regionally when the materials are readily available, and they can be used by cost-effective labor to produce structures that are both affordable to the buyer and profitable to the builder. The Architectural Graphics Standard provides the following benefits of using light-framed wood construction (Ramsey and Sleeper 2000):

1. Economy,

2. Architectural flexibility,

3. Contractor familiarity with the system of construction,

4. Small work crews can handle most wood members without special lifting equipment,

5. Cutting and fastening can be handled on site with hand or portable power tools, and

6. The skills needed for light-framed construction methods are easily learned.

These benefits can be applied with concrete masonry construction or light-framing methods using cold-formed steel in many instances.

In many cases, on-site construction methods are preferred. H+M Industrial EPC (2021) lists increased flexibility for changes after construction begins, renovation accessibility, and decreased logistical constraints as benefits of using on-site construction methods. Conversely, they name weather impacts, safety risks, decreased productivity, increased schedules, and availability of labor as the cons of using on-site construction methods. H+M suggests that on-site construction methods are most suitable for civil and concrete works, open work sites with few trades, and existing facilities that are congested (H+M Industrial EPC 2021).

One article reviewed discusses the risks associated with uncertainty in hybrid construction projects, which utilize both off and on-site construction (Arashpour et al. 2016). The authors claim that “the high failure-rate of construction projects is a result of underestimating the extent of uncertainty and risk. Construction projects are one-off enterprises with many stakeholders that rely on complex interactions of the external

and internal environments." The article puts forth weather conditions, quality of work, and safety as some of the uncertain conditions that can affect construction project risk. Conversely, availability of resources (equipment, materials, and labor), compliance of the manufactured elements with on-site conditions, and equipment failure are some of the uncertainties associated with off-site activities. Based on their analysis, the authors suggest that "risk of late completion in hybrid projects intensifies as a result of uncertainty combination in off-site and on-site construction. Project size and work quantities, organization's risk appetite, resource availability, and workflow variability are contributors to the risk of late completion in hybrid construction projects."

Most panelized construction systems available today would fit into the category of hybrid construction projects. Panelized systems are generally fabricated off-site to some degree. The degree of fabrication depends on the context of the projects served by the manufacturing facility. As discussed previously, the degree of fabrication for panelized systems varies. Some examples of typical panel offsite manufacturing units or subassemblies for panelized systems are structural framing only, open systems, closed systems, and unitized cladding systems.

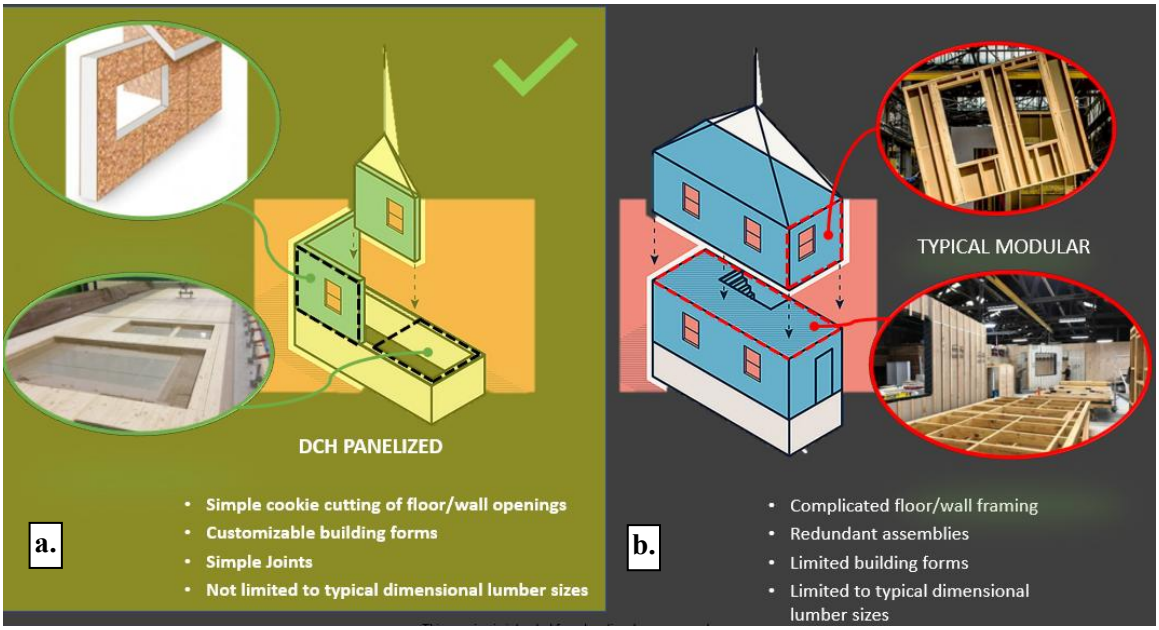

Figure 9. a.) Typical panel construction b.) Typical module construction.

2D panelized manufacturing units are finished to a lesser degree and have more joints in comparison to 3D modular units; however, they offer two distinct benefits. 3D modular units have well understood geometric restrictions and inherent redundant wall/floor/ceiling assemblies. 2D panels, as shown in Figure 9a, can better accommodate unique geometry in a building project and have increased material efficiency in comparison to 3D modules. 3D modules are six-sided; therefore,

redundancy will occur on sides having adjacent modules. For example, Figure 9b shows that when a module is stacked on top of another module, the upper floor assembly is stacked on top of the lower ceiling assembly. The same is true with adjacent walls. This leads to redundant assemblies and material waste. The degree of redundancy will depend on the module design. Additionally, if the redundancy is significant, valuable height or plan dimensional space can be lost.

Industrialized Construction–Manufacturing and Industrial Principles

There's an important distinction to be made between off-site construction and industrialized construction. Off-site construction just means made off-site and does not necessarily mean there are any productivity enhancements (Smith et al. 2023). Off-site construction is just one tool that can be leveraged to improved construction project efficiency. Effective implementation of other industrialized construction tools, such as DFMA, in a business model can also be considered for desired efficiency improvements.

It is important to understand that adding technology to a process does not necessarily guarantee efficiency gains. Technology can solve specific problems if it is assigned and implemented properly. Rupnik et. al (2022) discusses how allocating capital-intensive investments in digitalization and technology without fully considering and addressing the contextual frames severely diminishes the potential of the digital tools and techniques to deliver on the promise of housing affordability and accessibility. He goes on to say that leaping to digitalization and robotics without adopting the other changes to process and manufacturing principles required to improve efficiency have contributed to widely publicized offsite construction failures (Rupnik et al. 2022). In Figure 10, the authors suggest that technology should not be implemented until all other aspects of the business model, such as the context, the business platform, and the product platform, have been established.

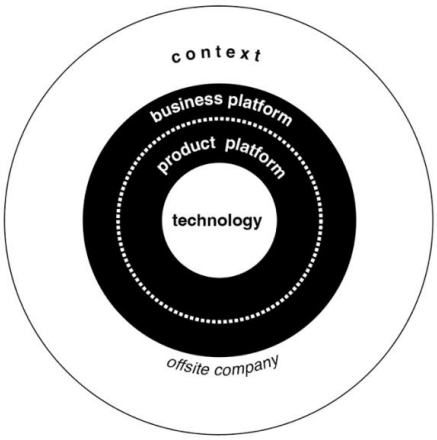

Figure 10. Conceptual nesting model of an off-site construction company (Rupnik et al. 2022).

One reason that the construction industry struggles with effective implementation of industrial construction principles is the nature of construction projects in comparison to the typical industrialized product. When one envisions a manufactured product, visions of repeatable objects, such as cars or appliances, typically come to mind. Construction projects typically do not, on the surface, produce repeatable objects. The products (buildings, or bridges, etc.) tend to be unique each time and often the series of activities utilized to construct the product change somewhat for each project. The definition of construction productivity implies that part of the challenge in improving productivity is learning how to effectively manage uncertainty and the need for unique customized solutions for each construction project. Literature suggests that elements from concepts/tools such as *Mass Customization*, *DFMA*, *Modularization,* and *Product Platforms* can be applied to construction projects to help introduce product flexibility and variability such that customized solutions can be conceived (Roxas et al. 2023; Smith et al. 2023; Gao et al. 2019; Jensen et al. 2018).

The construction process of industrialized buildings can be divided into 4 stages: design and planning, production and manufacturing, component transportation and inventory, and on-site assembling. It is suggested that industrialized construction can improve the efficiency of the process by simplifying the production and construction processes, reducing the number of steps, and reducing linkages between construction activities (Qi et al. 2021).

Lean construction has also been recognized as a tool that can be utilized for productivity enhancements and waste elimination in construction projects (Renz and Solas 2016; Bhawani et al. 2021; Howell and Ballard 1998). Lean construction has been implemented in construction projects historically to improve product delivery/performance, product quality, customer satisfaction, worker productivity, job site safety, risk management, sustainability, and profitability (Bhawani et al. 2021). A lean approach reduces complexity and uncertainty by reducing waste and non-value-adding activities throughout the entire value chain (Renz and Solas 2016).

One article reviewed (Howell and Ballard 1998) suggests that implementing lean construction means adopting a “project-as-production-system” approach. The same article advises that lean thinking can fundamentally change every aspect of project and company management; however, no one step-by-step guide can be offered, because the mental model level change required is a developmental process (Howell and Ballard 1998). Regarding construction projects, the following 4 core principles are offered:

- Alignment of resources, material and information flows,
- Coordination, and harmonization of takt speed,
- Just-in-time pull of resources and materials, and
- Continuous improvement of processes (Renz and Solas 2016).

"Lean" thinking in an organization potentially could be utilized to identify needs for modifications or innovations in the technology/materials/tools, process/operations, strategy/business model, and the people/organization/culture (Renz and Solas 2016).

Industrial management principles can be applied to on-site activities as well as off-site activities. Effective solutions may also consist of a combination of both (hybrid). Rupnik et al. (2022) tell us that the industrialized construction practices have their root in an early 19th-century American industry effort to increase the efficiency of mechanized production through improved management of *people, process, and data*. Rupnik et al. (2022) reference Guillén's "The Taylorized Beauty of the Mechanical" as the first study to link industrial management and construction.

Henri Fayol and Frederick Taylor are two pioneers in the study and development of industrial management philosophy. Managers in general are responsible for planning, organizing, staffing, directing, and controlling (Koontz and O'Donnell 1968). Industrial managers typically are responsible for managing the interaction of the 4 Ms. The Lean Enterprise Institute ("Four Ms" n.d.) defines the 4 Ms as:

1. Material—no defects or shortages.

2. Machine—no breakdowns, defects, or unplanned stoppages.

3. Man—good work habits, necessary skills, punctuality, and no unscheduled absenteeism.

4. Method—standardized processes, maintenance, and management.

In recent decades much research has been conducted and many technological developments have emerged to aid industrial managers in construction. The technologies can be classified into 4 main areas:

1. Business digitalization,

2. Computer integrated design,

3. Data acquisition, optimization, and predictive analytics, and

4. Robotics and automation (Qi et al. 2021).

Table 1 summarizes these technologies and provides an example of how they are applied.

Table 1. Industrialized construction technologies.

Technology	Application
Business Digitalization:	
Business Information System	Enterprise Resource Planning (ERP)
Self-designed System Integration	Cloud Database Platforms
Computer Integrated Design:	
3D and 4D Modeling	BIM
Design Optimization	BIM
Extended Reality	Virtual, Augmented, Mixed Reality
Data Acquisition, Optimization and Predictive Analytics:	
Optimization and Simulation	
Sensing Technology	Photogrammetry and Laser Scan
IoT Systems	RFID, GPS tracking
Advanced Data Analytics	Data Storage, Data Mining, Machine Learning, Deep Learning
Robotics and Automation:	
Digital Fabrication	CNC, CAD-CAM
Autonomous Machinery	Construction Vehicles/Equipment, Single-task Robots, Inspection Robots
Additive Manufacturing	3D Printing

Examples of Panelized Construction Systems

The contemporary business model for panelized products typically involves the unitization of the floor system and/or building enclosure components into 2D panels. These panels, once manufactured off-site, are typically erected at the site by the general contractor. In this section, several different types of panelized solutions will be discussed.

There is an important distinction to be made between manufacturing and fabrication that should be considered when reviewing these systems. According to Dictionary.com, “manufacturing” is defined as the making of goods or wares by manual labor or by machinery, especially on a large scale, whereas to “fabricate” is to make by art or skill and labor or construct. The distinction is that the term “manufacturing” is typically applied to repeatable large-scale production, whereas the term “fabrication” typically applies to custom, one-off components. For example, the

distinction can be seen with CLT panels, which is the first system reviewed. The CLT panels are *manufactured* into billets; however, they are *fabricated* into custom panels for a specific project. The terms can be applied similarly to SIP panels as well. The following sections include short descriptions of 7 popular panelized construction systems. The discussion for each is focused on how each system enhances efficiency through process, management, and design.

Cross-Laminated Timber (CLT)

According to the *CLT Handbook* (Karacabeyli and Douglas 2013), CLT is defined as a prefabricated solid engineered wood product made of at least three orthogonally bonded layers of solid-sawn lumber or structural composite lumber (SCL) that are laminated by gluing of longitudinal and transverse layers with structural adhesives to form a solid rectangular-shaped, straight, and plane timber intended for roof, floor, or wall applications (Figure 11). CLT is typically manufactured in 40-to-60-foot billets, which are later nested, and cookie cut into the required panel shapes.

Figure 11. Isometric view of a three-layer piece of CLT construction material (Wikimedia Commons contributors 2021).

As a building construction material, CLT is primarily used to prefabricate two-dimensional (2D) load carrying panels that are used as components in floor, roof, and wall assemblies (Karacabeyli and Douglas 2013). With proper design, CLT can be used in Type III, IV, and V construction, as classified by the IBC (International Code Council 2014). Examples provided in the 2021 *Mass Timber Design Manual* show CLT used as an alternative to masonry walls in multi-story residential or office buildings. Typically, it is difficult to attain economy with small scale projects; however, both the U.S. edition (Karacabeyli and Douglas 2013) and the Swedish edition (Borgstrom and Frobel 2019) also show examples of CLT being utilized for

the construction of single-family dwellings. An example of the erection of a CLT floor panel is shown in Figure 12.

Figure 12. CLT panel being installed on top of a CLT wall panel (https://www.sustainableconstructionservices.com.au/product/clt-glulam-design-installation/).

The involvement of the CLT manufacturers is typically limited to the provision of the required panels. They typically provide input to the design team when requested; however, their role is primarily that of a material supply company. The "just-in-time" delivery of the fabricated panels is coordinated with the onsite contractor for assembly at the project location. Figure 13 shows an example of the erection of CLT panels by on-site contractors, while Figure 14 shows a home constructed using CLT wall and floor panels. The panels shown in Figure 14 are nearly completely assembled.

Figure 13. Installation of CLT wall panel in new home (image by https://wigo.info/clt-prefab-houses).

One CLT manufacturer, SMARTLAM ("Strucutral Engineering and Design" n.d.), serving the commercial building market primarily with their two manufacturing facilities, describes the following process for the production of their CLT panel systems:

1. Project Design – Project management and design professionals assess needs such as product application support, budgetary guidance, design assistance services, on-site logistics planning, and complete conceptual through final construction documents.

2. Shop Drawings and Pre-Production Planning - After the project is contracted, the project manager works through important downstream considerations such as freight, onsite spatial constraints, installation sequencing, and more. 2D and 3D deliverables are made available for approval.

3. Manufacturing – The manufacturing process is carefully executed according to the project erection schedule and installation sequence. Design and installation sequences are discouraged at this phase.

4. Product Delivery – Confirms truck loadouts and delivery dates and times, reviews installation details and best practices with installers. Products are delivered to the worksite carefully wrapped and labeled for easy installation. Weights, shop drawings, and 3D visualizations are provided as aids to the installer.

Based on their webpage content, SMARTLAM appears to incorporate several of the industrialized strategies and technologies that were previously discussed. SMARTLAM advertises that they perform advanced CAD work modeling, can export/import IFC files for model coordination, optimize CLT panel nesting on standardized billets, work with direct digital output to CNC machinery, coordinate with trades on panel openings, and use DFMA as part of their workflow.

Figure 14. A home constructed with CLT wall and floor panels, mostly complete (image by https://www.pinterest.com/pin/277041814557884926/).

Structurally Insulated Panels (SIPS)

Sandwich style 2D panels can be constructed from seemingly endless combinations of skin and insulative material; however, the most common are the SIP panels which utilize OSB for the skin and expanded polystyrene (EPS), polyurethane, extruded polystyrene (XPS) or polyisocyanurate for the foam core. Figure 15 shows an EPS core wall SIP panel in the process of being installed. Production of SIPs is well regulated (American National Standard 2023) and prescriptive provisions have been included in the building code for some time now. SIPs were experimented with in the 1930s and 1940s; however, the industry expanded substantially in the 1990s, when CNC technology, such as shown in Figure 16, was adopted by the industry (Structural Insulated Panel Association (SIPA), n.d.).

Figure 15. Typical SIP installation. (This Photo by Unknown Author is licensed under CC BY-SA.)

As mentioned previously, the SIP industry is represented by both the APA and SIPA. Both associations produce ample resources for those interested in utilizing SIPs for their construction project. Pertinent to this report is their best practice guides on SIP shop drawings, SIP Fabrication/Manufacturing, and SIP Installation (Gould et al., n.d.). These guides provide insight on the industrialized construction strategies used by SIP manufacturers.

SIP shop drawings are typically required for building code and customer approval. Shop drawings also are required to instruct the production crew, as well as guide the assembly crew. The drawings are usually created from a 3D model created in-house based on the architectural plan. The designer will typically utilize the manufacturers' details and best practices to unitize the enclosure into efficient 2D panels. It is important to keep in mind that drawings can take several weeks to create in the front-end of the design and that this time should be recognized in the construction schedule. The best practice guide suggests that although significant time is required upfront, overall time and labor savings are achieved due to the prefabrication process.

Figure 16. Automated machinery used to construct SIP panels (Gould et al., n.d.).

Three levels (degree of manufacturing) of SIPs are offered amongst SIPA manufacturers. The first level of manufacturing consists of blank SIPs, which come in stock sizes of 4-ft-by-8-ft or 8-ft-by-24-ft. Blank SIPs are not cut in the factory and rely on the expertise of the contractor at the jobsite to cut to size. The second level of manufacturing consists of prefabricated SIPs, where the blank panels are cut to size in the factory using specialized cutting equipment. The third level of manufacturing includes a ready-to-assemble (RTA) SIP package. RTA packages differ than prefabricated SIP packages in that all the internal elements such as headers, bucks, and splines are preinstalled at the factory.

Figure 17. SIP panels being installed onto a timber frame (image by https://timberframe1.com/blog/stronger-faster-better-inside-story-structural-insulated-panels-sips/).

As with CLT panels, SIPs are typically not installed by the manufacturer. They are typically installed by the site contractor. Figure 17 shows the second level type SIP panels being installed on a timber frame. This type of installation is common for SIP panels. Timber frames provide efficient support systems for SIP panels. As mentioned previously, most SIP panels have load bearing capabilities. Figure 18 shows an example of a clear-span SIP panel being installed on a structural ridge beam and load-bearing SIP walls. It is common for SIP panels to be installed using readily available high-lift capacity forklifts rather than expensive cranes.

Many SIP installation practices have been standardized, and SIPA offers training programs such as online training courses, registered master builder and designer programs, SIPschool hands-on field training, Carpenters International Training Fund (CITF) for SIPs, and SIP manufacturer in-house training programs. The extensive training resources available would suggest that there are efficiency gains available in SIP home projects constructed by contractors having one or more of the listed certification programs.

Figure 18. SIP roof panel being installed on SIP wall panels and timber ridge (image by https://starcraftcustombuilders.com/addition2.htm).

Superior Walls

Superior walls are prefabricated precast concrete wall panels that are utilized for below-grade basement wall and sometimes above-grade wall construction.

Superior Wall products, such as the XI Wall shown in Figure 19, are insulated to meet the requirements of building code and beyond in some instances. One unique feature of the Superior Wall product is the use of 5,000 psi minimum compressive strength concrete. The use of high strength mix increases durability of the concrete elements and allegedly eliminates the needs for building code required damp-proofing. Another unique aspect of the panel design is the no-footing requirement. The superior wall panels are designed to bear on a crushed stone base rather than a concrete wall footing.

Figure 19. Superior wall XI wall product (https://www.superiorwalls.com/superior-walls-products/xi-wall-superior-walls/)

Superior walls offer several other advantages beyond those just named. One is the speed of construction. Superior Walls advertises that their walls are typically installed in less than a day in almost any weather conditions. Additional advantages include the ability to finish the interior side of the wall without additional framing, reductions of trades required onsite, quality control due to off-site production and reduction in stockpile space requirements due to just-in-time delivery. Currently, Superior Wall products are used primarily for single-family residential basements; however, their products can be used in commercial building applications.

The Superior Walls platform offers four main products to consumers: The XI Wall, The XI Plus Wall, the UI Wall, and the AG wall. These products consist of what can be considered several (manufactured) repeatable modules. The stud assembly that

includes the insulative stud form with rebar and the cold-formed steel interior stud, and the insulative facing. These modules can be uniquely combined to form custom foundation solutions. Superior Wall has typical in-house details to accommodate wall features like beam pockets and openings.

Figure 20. Superior wall panel being hoisted into place to construct a residential basement (https://www.wconline.com/articles/91186-housing-innovation-award-winner-starts-with-superior-walls-foundation)

Unlike CLT and SIP wall assemblies, the installation of the Superior Walls panels is performed by in-house crews and equipment. The experienced installation crew arrives at the site with the product and crane equipment to install the basement wall system. Both the pad for the walls and a pad for the crane must be properly prepared according to the Superior Walls specifications prior to the arrival of the installation crew (Walls 2022). Figure 20 shows a Superior Wall panel being hoisted into position as part of a residential basement. Residential basements are the primary market for Superior Walls; however, they do offer an above-grade product that can be stacked for utilization as the exterior wall of a home. Figure 21 shows an example of a home constructed using this stacked method of construction.

Figure 21. Superior wall panel utilized in a multi-story residential application (https://www.wconline.com/articles/91186-housing-innovation-award-winner-starts-with-superior-walls-foundation)

Bensonwood

Bensonwood is an industrialized builder that specializes primarily in the provision of residential, single-family construction. Bensonwood's vision involves bringing high performance, sustainable architecture to mainstream homebuilding. Bensonwood offers 4 brands of complete building products and has defined an overarching business platform, which serves all 4 brands ("Tektonkiks Advanced Building Components Standard Details and Design Rules for Architects Engineers, and Builders" 2023). The 4 brands are Unity Homes, OpenHome, Tektoniks, and their custom line of Bensonwood Homes. Figure 22 shows an example of a completed OpenHome residence (Lake-Flato option). The OpenHome brand provides aesthetically pleasing, functional homes designed by renowned architects.

The company has modularized a set of prefabricated building components that are utilized across all their brands to construct the homes within each brand. The 2D panelized components include standardized wall panels, roof panels, open cavity panels, and mass timber elements. The components are fabricated offsite in Bensonwood's climate controlled factory, where third-party inspectors certify each component as it is assembled ("OpenHome" n.d.).

Figure 22. Bensonwood OpenHome line residence (https://bensonwood.com/openhome/lake-flato/)

What sets the Bensonwood line of prefabricated housing component aside from other panelized product providers is their focus on enhanced energy performance and durability. Figure 23 shows a cross section of a high-performance Bensonwood wall panel. Note the additional depth of cavity achieved by utilizing engineered I-joist. The extra depth allows for improved cavity insulation levels. Also notice the rigid insulation installed on the exterior side of the wall and the stud assembly on the interior side. The interior stud furring cavities provide space for utilities branch lines to be installed. The extra cavity space also makes it easier to renovate in the future as needs change, which evidences the adopted open building philosophy of the company.

Figure 23. Cross section of a Bensonwood prefabricated wall panel (https://www.buildinggreen.com/blog/bensonwood-reinventing-house).

Figure 24. A Unity Home, using the Varm platform, under construction (https://unityhomes.com/how-we-design-build/).

Unity Homes, offers consumers 5 standardized predesigned housing platforms to choose from. The platforms have been optimized for cost and performance, and prices typically range $250,000-$800,000. Components such as additions and porches can be selected from a library of predesigned modules and added on during the design

process. One of the platform offerings is shown under construction in Figure 24. Figure 25 shows an example of assembly of predesigned modules in the digital model. The consumer selects the platform they like, and the Unity Home designers configure the platform, using the standardized components, based on site, program, and budget requirements. Unity homes offers two packages within the platform: the Shell and Tempo. The Shell package only includes the high-performance building envelope, and the Tempo package includes most of the finishes. Unity will install the enclosure package using their own crews; however, the finish and foundation are completed using local contractors.

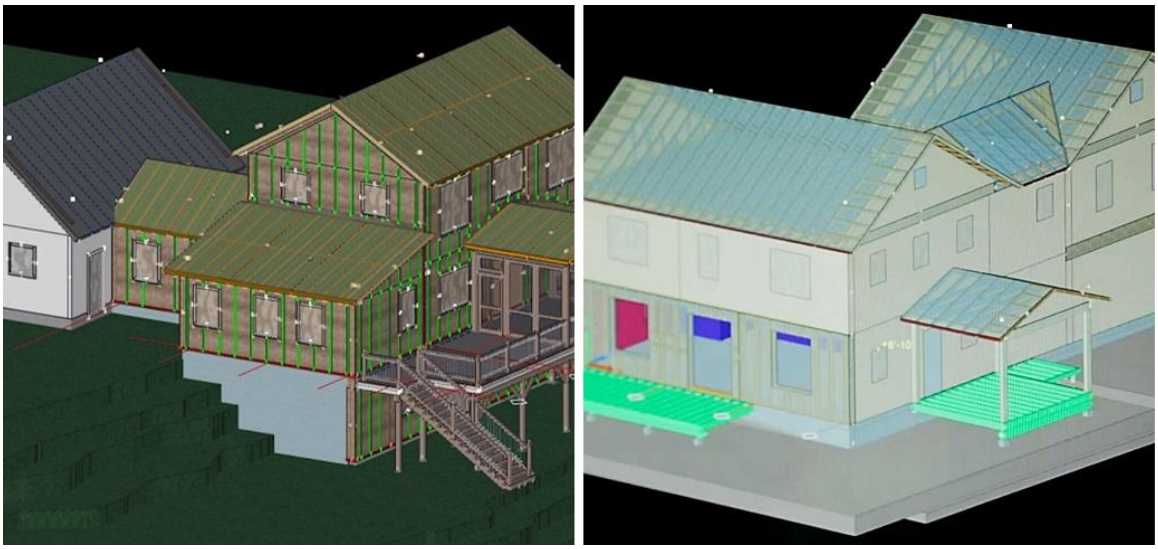

Figure 25. Predesigned Unity homes modules being assembled in the digital model to form a unique custom home (https://unityhomes.com/how-we-design-build/).

The OpenHome line of structures offers three predesigned platforms, designed by renowned architecture firms, to consumers. Consumers make selections based on aesthetic preferences and square footage requirements. These homes typically cost greater than $1,500,000. After selection of the platform, the consumer is guided through a design process by the partner firm, which is economized to avoid design fatigue. Consumers can typically customize finishes and fixtures and the builder also offers semi-custom design services if required. Interestingly, the exterior doors, interior doors, stairs and trim are crafted at the Bensonwood fabrication facility as well. When design is complete, the enclosure/frame is panelized and constructed at the fabrication facility. As with Unity Homes, Bensonwood assembles the enclosure onsite upon completion of the foundation (by others) and works with the consumer to select a builder for the remainder of the construction.

Builders can also partner with Bensonwood and access the Tektonic platform, that provides components to all Bensonwood brands, to construct their own high-performance custom designs. A guide is provided to potential builders interested in

this program (Bensonwood, n.d.). Standards and guidelines are provided such that critical manufacturing, shipping, or site logistics requirements are not violated. Bensonwood standards are divided into core standards that cannot be violated and strongly encouraged voluntary best practices, which they are calling partner standards. Adherence to the standards ensures that optimized performance, cost-effectiveness, and schedule priority is achieved. The standards are summarized in Table 2.

Table 2. Bensonwood Tektoniks Standards.

Core Standards	Partner Standards
Standard wall, floor, roof assemblies	Best practices for 3D modeling
Standard maximum panel heights	Adoption of the OpenBuilt Design Rules
Typical Engineering restrictions	Adherence to the Master Grid
Standard window brand selections	All windows and doors sized and located
	Use of standardized components

As mentioned previously, Bensonwood relies on the use of standardized wall, floor, and roof assembly components to service the various building platforms they offer. By using standardized components, they can achieve economy of scale manufacturing benefits through repeatability of the manufacturing unit and avoidance of retooling operations. Through incorporation of these repeatable 2D panels into their creative platforms, they can offer consumers some degree of product variety within the standardized products. Figure 26 shows the cross section of two of their wall panel assemblies.

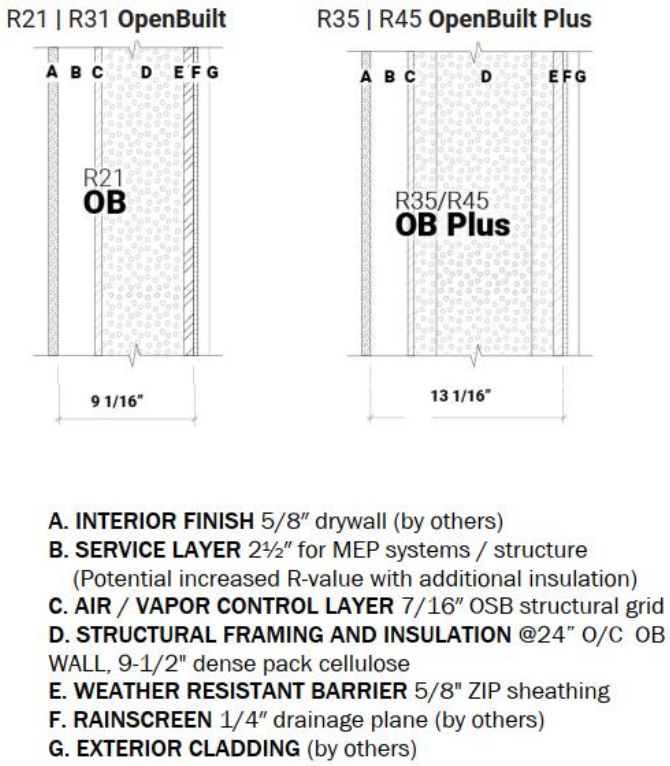

Figure 26. Tektoniks OpenBuilt wall panel ("Tektonkiks Advanced Building Components Standard Details and Design Rules for Architects Engineers, and Builders" 2023).

Panelized Roof System

A panelized roof system generally consists of wood-framed subassemblies that bear on purlins, which in turn bear on girders. The girders are supported on the interior by columns and are typically supported on the exterior by concrete masonry (CMU), cast-in-place concrete, or tilt-up bearing walls. According to the Engineered Wood Association (APA), the two most common panelized roof options are the all-wood system (Figure 27) and the hybrid panelized roof system shown in Figure 28 (APA-The Engineered Wood Association 2006). In the all-wood roof system, glulam girders and either I-joists, wood trusses or composite purlins are used to support the wood-framed subassemblies. An example of an all-wood system is shown in Figure 29. In hybrid systems, steel joists and joist girders serve to support the wood-framed subassemblies. In both systems, the wood-framed subassembly is the same.

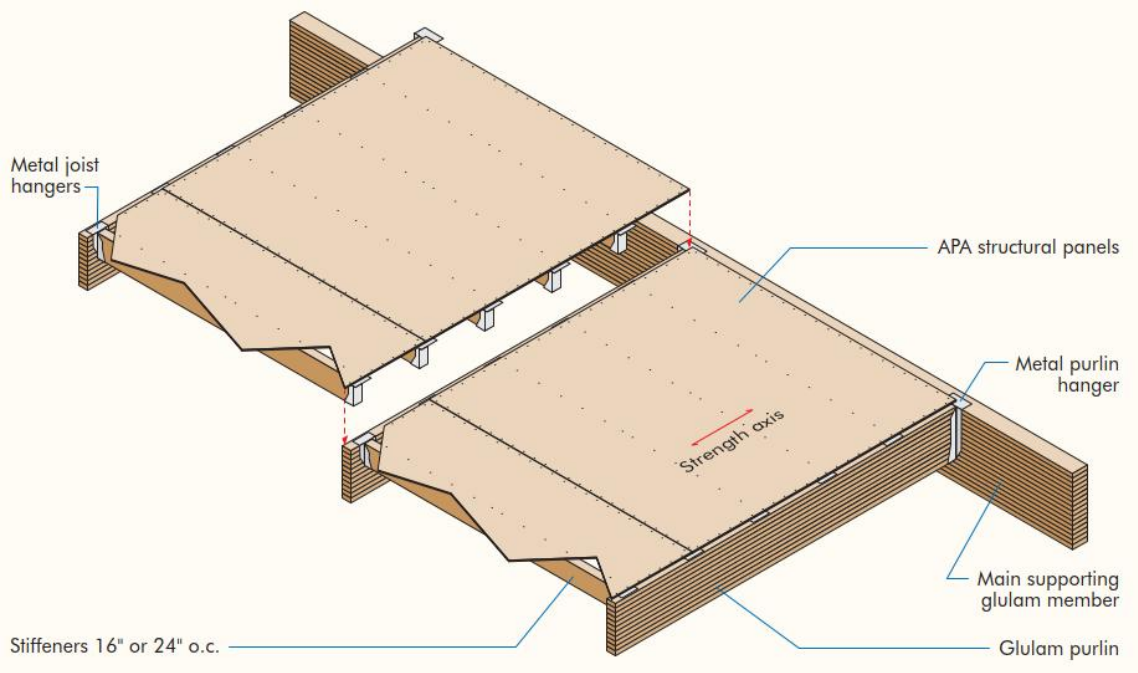

Figure 27. Typical All-Wood panelized roof system (APA-The Engineered Wood Association 2006).

The wood-framed subassemblies are the repeatable unit in the system, which can either be constructed on-site or off-site (WoodWorks 2012). The subassembly consists of 2x4 or 2x6 sub-purlins (stiffeners) sheathed with wood structural panels. The subassemblies are typically 8-ft-by-8-ft or larger, depending on the required geometry and available sheathing sizes. As shown in Figure 28, the subassemblies are fastened to one purlin, which in this case is a steel joist, on-site using hangers, and the entire panelized unit is installed using equipment, such as the high-lift capacity forklift shown in the figure.

Figure 28. Hybrid subassembly consisting of the wood-framed panel and on steel joist being lifted into position for installation (https://www.dukepacific.com/services/panelized-roof).

Panelized roof systems are typically utilized for low-sloped roof commercial structures such as big box stores or warehouses. This system has shown to be a cost-effective alternative to steel construction. Typical savings range between $1.25 to $1.50 per square foot over steel-joist and metal deck systems constructed in the western regions of the U.S. (WoodWorks 2012). The APA presents a case study (450,000 ft^2 building) in which the installed cost of an All-Wood panelized roof structure was $4.85 per square foot and another in which the installed cost of a Hybrid panelized roof structure (51,500 ft^2 building) was $4.50 per square foot (APA-The Engineered Wood Association 2006). In addition to the cost-effectiveness, panelized roof systems are used to improve project safety and also accelerate construction. It is claimed that an accomplished erector can install 100,000 square feet of roof panels per week (WoodWorks 2012).

Figure 29. Hybrid subassembly consisting of the wood-framed panel and on steel joist being lifted into position for installation (https://www.dukepacific.com/services/panelized-roof).

In comparison to some of the other panelized systems discussed in this section, this system is relatively low-tech; however, it can be seen by the popularity of the system and its proven cost-effectiveness that the success of a particular panelized system is not necessarily directly correlated with the complexity or technology associated with the system. Interestingly, most, if not all (in some cases), of the assembly of the panels is conducted on the site. What is also interesting about this system is the efficiency of the 1D components. Prefabricated members such as glulam beams or wood trusses are economized and have little material redundancy.

For this system, the product platforms can be divided into the All-Wood system platform and the Hybrid system, which are modularized into the wood-framed roof assembly (2D subassembly) and the girder-purlin framing system which consist of repeatable prefabricated 1D or 2D assemblies that can be reconfigured or adapted to the customized project.

Light-framed Panels

Light-framed panels are typically what comes to mind when someone mentions panelized construction. Buildings constructed with this type of panel most closely resemble those constructed using traditional, on-site, light-framing methods. As mentioned previously, the panels are generally constructed from light framing such as wood or CFS and are assembled as a platform framing system.

Light-framed panels can be constructed as open or closed panels. As mentioned previously open panels are fabricated for delivery to the project location with one side of the wall panel open whereas closed panels arrive with both sides covered such as the one being craned into place in Figure 30. Closed panels offer an increased degree of fabrication at the cost of additional front-end design and coordination, as well as a decreased ability to make field changes once production on the panels has begun.

Figure 30. Closed wall panel being lifted into place (image by https://www.timber-frame-suppliers.co.uk/closed-panel-timber-frame-system/).

Increased use of closed panels for the building enclosure is one way the AEC community is responding to the increasingly demanding requirement of the modern building and energy codes (Mitchell 2021). They are sometimes used for the purposes of providing a high-performance building envelope; however, as in the case of a unitized building enclosure system, it is often a challenge to ensure continuity of the components and membranes at the joints.

ACQBuilt Inc., a Canadian panel manufacturer, has been in operation over 22 years. The company utilizes their state-of-the art manufacturing facility to produce prefabricated panels and modules that are utilized to construct primarily residential structures. Figure 31 shows a second-story wall panel being set in place for the construction of a single-family residence.

The builder uses their specialized construction process to increase construction predictability (decreased risk), decrease the need for short term staffing, reduce administration and marketing resources required, reduce waste, decrease carbon-footprint, and deliver a higher performance home. In addition to these standard off-site construction benefits, they advertise that they help builders complete their projects

faster, more efficiently, and at a higher level of quality through incorporation of the following ("Builder Benefits" n.d.):

1. Off-site facility allows for faster cycle times, which reduces associated building soft costs, such as interest, taxes, power consumption, and equipment rental.

2. Off-site production avoids construction element exposure to weather.

3. Precision building method elevates the quality and precision of the structure, leading to higher customer satisfaction and less rework in the field.

4. Off-site production helps to limit cost overruns and trade trip charges.

5. Innovative building process helps to increase building capacity but not incremental overhead.

6. The company values clean job sites, a safety focus, professionalism, and superior service.

The company employs a diverse group of trained professionals that allow the company to manufacture turnkey building products in some instances. For example, they employ certified journeymen, in-house 3D modeling technicians, city permitting professionals, and in-house professional tradesmen that help manufacture the floor, wall (including doors and windows), and roof assemblies.

Figure 31. Open wall panel being lifted into place (https://vividribbon.ca/acqbuilt/).

ACQBuilt uses centralized framing in a state-of-the-art, automated, climate-controlled plant instead of on-site construction to produce their panels. ACQBuilt claims in a video that their centralized production reduces waste and inefficiency by over 50% (Homes 2018). Figure 32 shows an example of a piece of computer-controlled equipment installing fasteners in a panel assembly. A high level of technology is utilized by ACQBuilt. Their state-of-the art production facility uses the most advanced cutting, shaping, nailing, and inventory control equipment to build the panels.

Figure 32. Fastener installation using state-of-the-art equipment in ACQ plant (Homes 2018).

ACQBuilt utilizes a 4-step build process ("Builder Benefits" n.d.), which includes the pre-construction phase, the offsite construction phase, the logistics phase, and the onsite assembly phase to deliver mostly complete buildings (including finish items if required). During the pre-construction phase, a 3D digital model is created and programed into automation software, which decomposes the building into components that can be easily fabricated. According to ACQBuilt, this design-build process provides flexibility of design, which gives them the ability to manufacture more complicated structures. Simultaneously, during this phase, design drawings for permitting and material quantities for estimates are also extracted from the model.

Panel framing begins with the sorting and selecting of engineered lumber from their inventory. The facility utilizes real-time inventory software to track inventory as it is moved through the production process, which allows them to make more efficient bulk purchases of construction materials. Construction materials are then moved

through a mechanized process using automated equipment, such as the vacuum lift shown in Figure 33, to create wall, floor, and roof panels. In addition to wall, floor, and roof panels, ACQBuilt has the capability of producing stair, deck, and other custom auxiliary components.

After panel construction is complete, the panels are moved to trucks in a coordinated manner for shipping to the jobsite. This kicks off the logistics phase. Once loaded for transport, real-time scheduling is used to ensure that panels are delivered in the right order and just-in-time for erection.

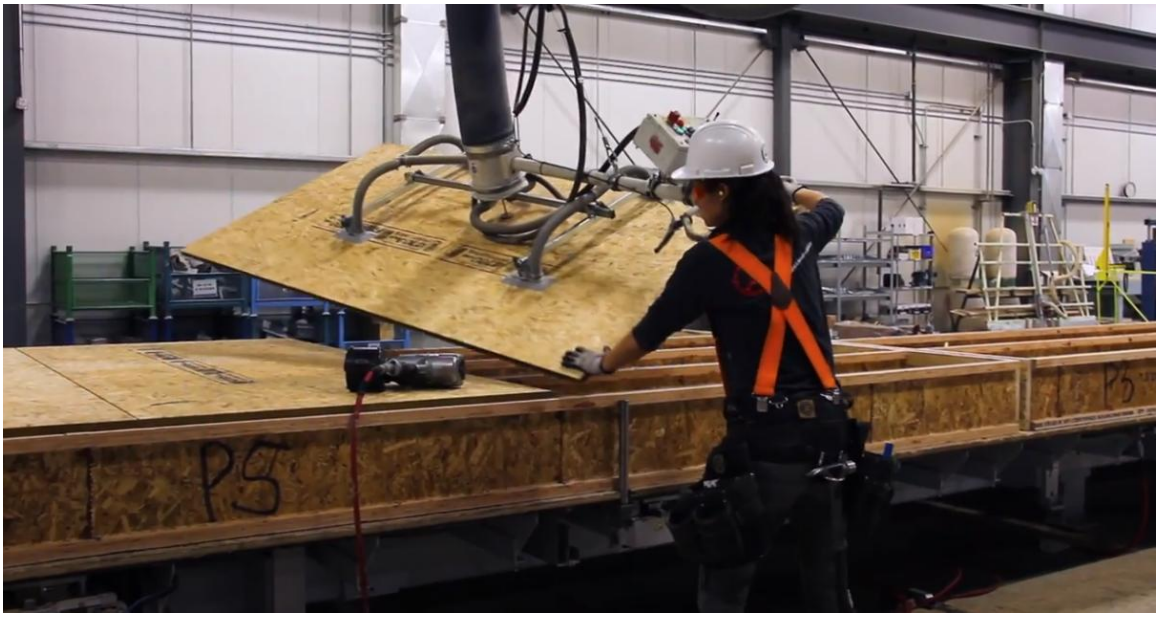

Figure 33. Vacuum lift moving OSB subfloor to installation location (Homes 2018).

ACQBuilt utilizes its own erection crews to assemble the panels to form the final structure. ACQBuilt uses its own equipment and has a crew to perform unloading operations and a separate crew to focus on assembly. The company implements precision site organization and component sequences to ensure crews can efficiently assemble the structure. The experienced crews perform synchronized simultaneous tasks to reduce the manhours and resources required to construct a building. The company claims they can erect a typical single-family home in approximately 6 hours, with a few additional hours to finalize the building exterior finishes.

Curtain Walls

Curtain walls are defined as thin, usually aluminum-framed walls, containing in-fills of glass, metal panels, or thin stone (Vigener et al. 2016). Alternative materials such as wood can also be utilized for construction of curtain wall framing. Figure 34

shows an example. Curtain walls are generally utilized for provision of the exterior wall portion of the building enclosure. Curtain walls are self-supporting; however, they typically do not transfer building primary framing system gravity loads. They are attached to the building's primary structural frame at the floor and roof levels and transfer out-of-plane wind loading to the lateral force resisting system at those points.

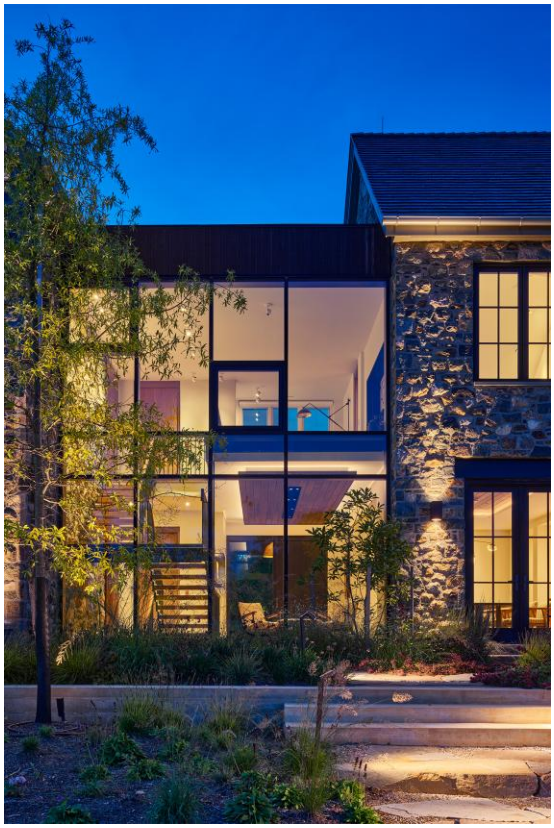

Figure 34. Timber curtain wall system used in modern home (image by https://www.loewen.com/curtain-wall/).

Curtain walls can be divided into stick systems and unitized or modular systems. Curtain wall systems are typically utilized for commercial applications, such as the building shown in Figure 36; however, the use of curtain walls can also be seen with modern residential design, such as the one shown in Figure 35. Stick systems are field framed using 1D components; alternatively, modular systems consist of larger unitized 2D subassemblies that are shipped assembled to the project location. The unitized modular units are assembled in the factory and shipped to the site for installation by the glazing contractor (Vigener et al. 2016). Advantages of unitized units include increased factory seal reliability, reduced cost of factory labor (compared to field labor), the assembly of modules occurs simultaneously with erection of

structural frame, less stockpile space is required, and the time required to enclose a building is greatly reduced.

Figure 35. Modern residential home constructed using curtain walls (image by https://wfmmedia.com/curtain-wall-system-modern-house-designs/).

The curtain wall industry is well established, and high levels of quality control and planning are typically implemented to ensure durable and high-performance enclosure systems. High quality materials are utilized, and mock-ups are usually tested prior to assembly of the modules that will be utilized for the project. Significant effort and resources are required to produce curtain wall systems, and the cost to the consumer is often high.

An example of a unitized curtainwall system by Mitek is shown in Figure 36. MiTek utilizes its skilled project management team to coordinate the delivery of its curtainwall products. The MiTek process includes industrialized activities present in the pre-construction, design, production, and installation phases ("Our Process" n.d.).

During pre-construction, expectations and milestones are set to facilitate on-time delivery of the cladding system. MiTek team members work closely during the early stages of design development to ensure that aesthetic, functional, and logistical concerns are addressed. Experience has proven to them that early coordination helps mitigate cost increases and schedule extensions.

Figure 36. Benson curtain walls installed on Alcoa world headquarters (https://www.bensonglobal.com/portfolio-item/alcoa-world-headquarters/).

During design, factors such as the design loading, air and water control, code compliance, glass selection, material finishes, daylight harvesting, window treatments, structure and cladding system movement, anchorage, window washing, and re-glazing are all considered to ensure a high-performance system. Also included in the design phase is the construction of a visual and performance mock-up.

MiTek utilizes its refined industrialized product delivery process to produce essentially one-off customized products economically. Elements of mass customization and DFMA philosophies can be seen interwoven in the process. MiTek states, “Our vertical integration process gives the engineering, manufacturing and installation teams the ability to create system designs that synchronize aesthetics, performance, and efficiencies throughout fabrication, manufacturing and installation” (“Our Process” n.d.). Investopedia defines a vertical integration strategy as one that allows a company to streamline its operations by taking direct ownership of various stages of its production process rather than relying on external contractors or suppliers (Hayes 2024). By vertically integrating and fostering relationships with suppliers, MiTek can directly influence input material quality and schedule, which can potentially decrease project risk.

Two additional risk mitigation strategies occur in the production phase. The first entails fabrication of new extrusion dies to ensure error free production of framing components. The second occurs prior to assembly of the modular unit, when the framing is preassembled without glass or sealant to determine if any adjustments are required and to ensure the highest level of workmanship.

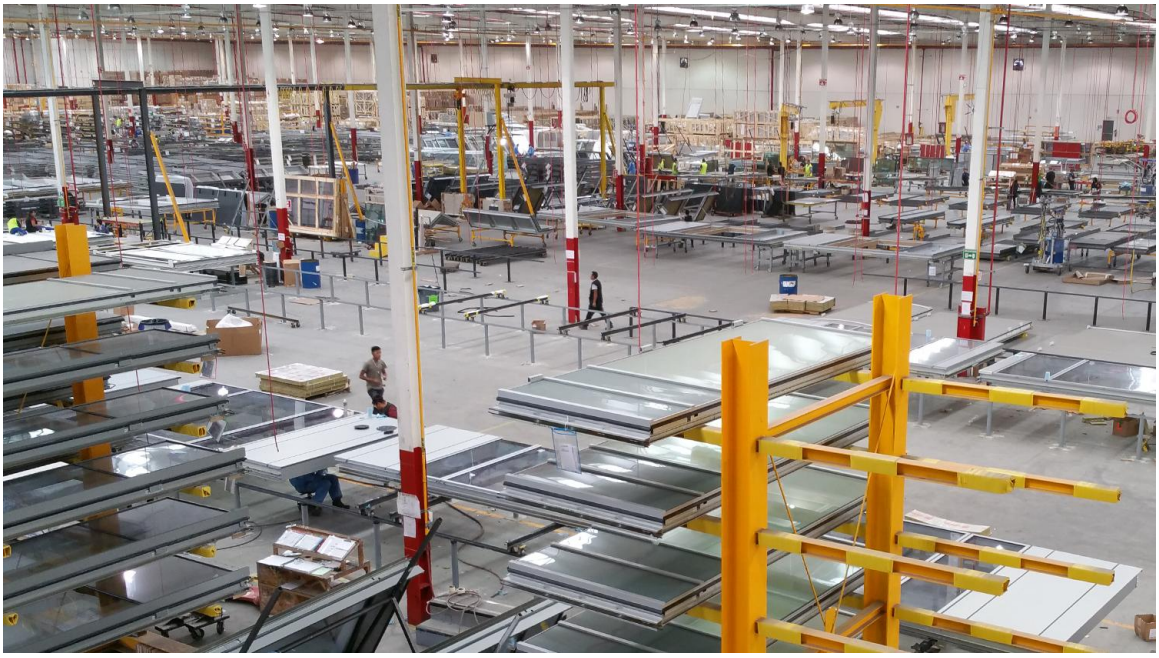

Figure 37. Benson curtain wall fabrication facility (https://www.bensonglobal.com/).

The panels are fully assembled in their 300,000 square foot indoor fabrication facility (Figure 37). The facility is arranged in a manner such that it can be easily reconfigured to accommodate new workflows. The company utilizes specialized software to track inventory, in-progress production, real-time production rates, and other data metrics, which are utilized for supply chain order control and project management scheduling.

Curtain wall quality control is rigorous. As mentioned previously, MiTek implements their vertical integration strategy to help ensure quality of the 2D modules input material. In their description of the quality control process ("Our Process" n.d.), they emphasize the importance of catching or avoiding errors early on in the process. They want to ensure that materials are fabricated, shipped, transported, and stored properly so that they can reduce in-plant rejection rates and honor schedule and quality control commitments. In addition to supply chain control, in-plant quality control programs are implemented to ensure dimensional accuracy, silicone adhesion, strength and viscosity, paint thickness, color matching, and air and water integrity. After production, a peelable protective coating is applied to the scratchable 2D module components. The units are then shrink-wrapped and crated for shipping.

The units are subsequently shipped to the jobsite for installation. Transportation planning is conducted to determine the staging of sequential unit delivery, efficient hoisting strategies, site constraints, module site storage, and methods of installation. If needed MiTek offers site and installation services to ensure successful, timely installation, as well as to help diagnose and implement solutions to unforeseen installation problems.

Discussion of The Seven Panelized Systems

Seven panelized construction systems were reviewed in the previous section to introduce a selection of popular systems available to consumers in the modern construction market. All systems unitize some or all of the building to achieve the benefits discussed in this paper. Most of the systems leverage off-site construction facilities to centralize panel construction activities, in order to achieve efficiency/managerial enhancements in one or more of the 4 m's discussed earlier: Material, Machine, Man, and Method. There were similarities in how they achieved economy; however, their production approaches, degree of prefabrication, and panelized product offerings to the consumer differed. Following is a discussion about the successful elements and ongoing challenges recognized in the 7 reviewed systems. All the manufacturers mentioned in the previous section have had success in their respective markets. It is important to study those aspects that have brought about this success and also to identify areas for improvement for future iterations of similar business models.

Centralized production of construction products offers obvious benefits; however, there is a caveat. Notably, manufacturers with off-site facilities typically have large space and labor requirements to maintain operation of their facility. These requirements inherently increase product overhead, which drives a need for steady consumer demand and can lead to volatile business conditions. Most, if not all, the manufacturers of the panelized systems reviewed, offer products that are customized, one-off types, which are not easily stockpiled for future distribution. The danger in this customized approach is that without continuous demand, the manufacturer cannot sustain its operation. Even a short absence of consumer demand can put off-site manufacturers out of business (A. C. Jellen 2015). Some manufacturers, rather than ceasing operations, respond to low consumer demand with employee layoffs or cuts. Others that rely on subcontractor support can buffer periods of slow demand by simply not hiring; however, the downside to this approach is increased uncertainty due to subcontractor reliance during all times.

Several of the panelized systems, such as CLT, SIPs, and the curtain wall system, appear to rely mainly on consumer-centric, mass customization solutions in their business models. CLT and SIP systems have basic manufacturing units of billets and blank panels, respectively; however, without demand, they can only stockpile a limited amount of these without risking material purchasing problems.

Overreliance on mass customized solutions is a double-edged sword. In one regard, having the ability to customize the product offering to support one-off applications introduces flexibility in the business model to serve a more diverse group of markets. This flexibility improves access to an increased number of consumers. Conversely, the high overhead required to create a mass-customized, off-site solution can create a condition where the manufacturer may have little capacity to weather slow economic periods in the construction markets they serve.

Utilizing tools like DFMA and platform thinking in the product planning stages to effectively modularize products into manufacturable units that can be utilized in a diverse group of products can potentially help to mitigate the risks associated with

a manufacturing business. For example, Bensonwood has developed an overarching business platform in which one manufacturing facility serves 4 individual platforms. The individual platforms are governed by associated rules that provide for both efficient manufacturing of a repeatable module, such as a wall or roof assembly, and product variability within the platform. The company serves primarily the single-family residential market, which is a risk if there is a downturn in this market; however, they mitigate the risk by serving different tiers within the market with their 4 brands.

The panelized roof system providers take a different approach to risk management. Whereas ACQBuilt utilizes state-of-the art equipment and advanced process monitoring techniques such as inventory control to achieve improvements in quality and efficiency, the panelized roof providers leverage simplified process and low overhead to achieve cost saving in comparison to its main competition (steel roof deck systems). This does not necessarily mean that the panelized roof systems are less industrialized in comparison to the light-framed panels produced by ACQBuilt. On the contrary, one can argue that the process is more industrialized with the proven cost-savings as the evidence.

Wooden light-framed roofs are, in general, efficient structural systems. There has been a significant level of industrial development, prior to incorporation into other platforms, that has already been achieved in light-framed construction systems. Primarily, wood has proven cost-effective in most cases where building code allows its use, and additionally, prefabricated members such as trusses and composite framing, are economized by the manufacturer during the design phase. There is little material waste in a wood light-framed structural system. Typically, all members have high utilization ratios in the structural system. This is not always the case with systems such the CLT panelized systems. Often, especially when utilized as walls, the panels have low utilization rates because of the slab nature of the product (A. Jellen and Memari 2022).

The panelized roof system has two standard platforms that are modularized to use the same light-framed roof panel. The system is simple and flexible enough that the repeatable roof panels can be manufactured on-site or off, depending on the economy of the project. Additionally, the system is adaptable, and the assumed risk can be raised or lowered based on the appetite of the contractor and the perceived reward. For example, a high-risk, off-site, vertically integrated approach could be adopted where all the panels and/or prefabricated wood members are produced off-site and transported to the project location for erection by in-house erection crews. Alternatively, a risk adverse general contractor serving a region with inconsistent consumer demand might implement a site-built, horizontally integrated approach where all the panels would be constructed on-site using materials provided by others and erected using subcontracted crews. Both approaches could be equally successful and efficient depending on the regional business context and management of the operations.

The panelizers reviewed differed in their approaches to panel installation. Some, like Bensonwood, ACQBuilt, and Superior Walls, install all their products using in-house erection crews and their own equipment, whereas most CLT and

curtainwall providers do not typically perform the installation but offer technical services and sometimes installation services if required. It is important to recognize, however, that even if CLT and curtainwall providers do not perform the installation, they still provide detailed instructions and drawings and are almost always immersed in the coordination and staged delivery of the panels to ensure installation success.

One aspect of the curtainwall production process that stood out in comparison to what the other panelized manufacturers were providing was their attention to quality control (QC). QC and error identification seemed to permeate through all manufacturing phases. For example, MiTek incorporates the following into their process: early coordination with stakeholders is conducted in the pre-construction phase to reduce cost-increases and schedule extensions, the construction and testing of visual and performance mock-ups during design, control over quality and schedule of input material through vertical integration of suppliers, construction of new extrusion dies for each project to ensure high quality, pre-assembly of framing prior to production, in-house QC programs to ensure dimensional accuracy, silicone adhesion, strength and viscosity, paint thickness, color matching, and air and water integrity, and the application of protective coatings to scratchable surfaces to protect products during transport.

All the panelized systems reviewed aim at providing high-quality, high-performing, economical products to consumers in their markets. Various industrialized tools and philosophies, as well as management practices, are incorporated into each of the companies' processes. Each has its own set of practices and processes that work for them in their respective markets. Table 3 summarizes the panelized systems that were reviewed and compares various industrial aspects of the systems.

Table 3. Comparison of the panelized systems reviewed.

System	Mfg. Unit	Install Typical	Unique Aspects of System/Company	Degree of Prefabrication	Comparative Cost
CLT	40'-60' Billets	No	Nesting Routines	Low	Medium
SIP	Blank SIPS	No	Installer Training Programs and Codification	Low	Medium
Superior Walls	Stud Assembly	Yes	Product design, Reduction of Trades	Low	Low
Bensonwood	Wall, Roof, Floor Pack	Yes	Platform design	High	High
Panelized Roof	Roof Assembly	No	Low overhead, on-site capabilities	Low	Low

LF Panels	None (Custom)	Yes	State-of-the-art technology	Low-Medium	Medium
Curtain Walls	None (Custom)	No/Yes	QC program	Low	High

Conclusions

In this paper panelized construction is discussed in terms of how it fits into the PPMOF and industrialized construction context. In recent decades many terms have been applied and misapplied when discussing the prefabrication of building elements. To avoid confusion, definitions of important terms from reputable sources have been provided at the beginning of this paper.

In simple terms, panel manufacturers are those who unitize building components and assemblies into 2D panels. The 2D panels are prefabricated to some degree, ranging from framing only to complete wall assemblies including finishes. Although the manufacturing process can, and in many instances does, occur off-site, panelized construction does not automatically imply off-site manufacturing. Manufacturing can just as readily occur on-site, such as with panelized roof systems or in mobile factories located near the project site if economical. Additionally, the end products in panelized systems are 2D panels that are assembled in the field to form the larger structure; however, this does not necessarily mean that the manufactured unit is a 2D panel. In many instances the repeatable manufactured units more closely resemble 1D elements, such as the wall studs in the Superior Wall system or the beams in the panelized roof system.

Panelized construction methods are not appropriate for all projects. Generally, consumers choose to utilize a panelized solution to reduce uncertainty in the schedule or with labor. To recap a few other potential benefits, panelized construction has also been used in the past to accelerate the construction schedule, improve worker safety, improve quality of product, reduce theft or vandalism, or reduce construction soft costs such as equipment rentals or loan interest. Although cost-savings do occur in some instances, they are generally not guaranteed. Efficiency gains are often offset by the high overhead costs of operating a facility and transporting panels to a project location.

In many instances offsite construction projects do not realize other claimed benefits available to users of off-site construction methods. To name a few, inefficiencies occur when projects are not originally envisioned as a panelized structure, manufacturer rules are not adhered to, or design changes are made after production has started. When inefficiencies occur, the problems can typically be associated with management of the project rather than with the product manufacturer. Most problem occur due to the project team's failure to assess and manage risk and uncertainty in the project.

As noted earlier in the paper, one article describes failure in construction projects as follows, "the high failure-rate of construction projects is a result of underestimating the extent of uncertainty and risk. Construction projects are one-off

enterprises with many stakeholders that rely on complex interactions of the external and internal environments." The construction process is affected and requires modification when prefabricated elements are introduced from both the perspective of the builder and the manufacturer. Industrialized construction philosophies and tools have been used by both to adapt to this circumstance. In many instances, the builder's site-built business model is inadequate to handle the introduction of prefabricated elements and must be reworked in order to achieve gains in efficiency. One author suggests that we utilize a "project-as-production-system" approach to aid in the industrialization of construction activities.

It is important to recognize that industrialization of a construction project does not necessarily involve mechanizing, automating, or digitizing operations; rather industrial construction tools and philosophies, such as DfMA, platform design, modularization, and lean thinking, generally help a business to simplify, manage properly, remove wasteful and non-value-added activities, continually improve, achieve thoughtful design of manufacturable products/units, identify their business context, properly define an appropriate business model, and also assess and manage risk/uncertainty better in their respective markets.

The incorporation of 2D panelized systems can potentially improve productivity of a construction project; however, any productivity gains realized through selection of the prefabricated system can be easily offset by inefficiencies in the remainder of the construction process. Based on the articles reviewed for this paper, it seems that there is opportunity for growth in the field of industrialized construction for both the builders and the prefabricators.

On the builder side of the equation accepting a "project-as-production-system" approach and adopting industrialized philosophies can lead to new perspectives and methods of construction such as those we see at Bensonwood. By clever definition of their platforms and modularization of the assemblies, they are able to offer high-performance, high quality, aesthetically pleasing products at similar pricing to their site-built competitors.

On the prefabricator side of the equation, there seem to be opportunities to develop new product platforms and improvements in process to help reduce production costs and mitigate risk in their business models. All the panelized manufacturers reviewed in this paper have been able to incorporate many of the industrial tools discussed in this paper to improve product quality and increase production efficiency in comparison to their site-built counterparts; however, the costs of many of the panelized solutions still tend to be above or comparable to the site-built version. Additionally, as discussed previously, there is risk due to high overhead/start-up costs that potentially can be reduced through increased industrialization.

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