Integrating Energy Efficiency Strategies with Industrialized Construction for our Clean Energy Future

Preprint

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Integrating Energy Efficiency Strategies with Industrialized Construction for our Clean Energy Future

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ABSTRACT

NREL's Industrialized Construction Innovation Team has developed an ambitious plan to accelerate the integration of energy efficiency (EE) strategies with Industrialized Construction (IC). The United States (U.S.) construction industry is beginning to use IC methods to build multifamily apartment buildings to address affordability and labor shortages. Apart from reducing cost of construction and delivery times, the IC method of permanent modular construction has the potential to facilitate the integration of a wide range of EE strategies and advanced controls into such buildings. While there may be unintended EE benefits to IC such as a tighter envelope due to higher construction quality, the process has not been leveraged specifically to enhance EE. NREL aims to claim this missed opportunity and integrate IC benefits with EE as well as advanced controls, distributed energy resources, and grid-friendly design strategies.

The paper proposes an 'IC Assessment Framework' to achieve affordable zero-energy modular multifamily buildings. Through the selection criteria of Design for Manufacturing and Assembly, the framework aims to distill a broad range of proven EE strategies for site-built into a set of strategies that qualify as easy to integrate for off-site. The output is a Factory Information Model (FIM) that represents a process-based digital twin to enable advanced time-and-motion study, plugs into open source building energy modeling platform (EnergyPlus), and serves as a vital tool facilitating wider adoption of EE integration. Conclusively, the paper delineates next steps for upcoming pilots with NREL's IC partners towards developing a transformational pathway for our Clean Energy Future.

Background

Need for Industrialized Construction in the U.S. for affordable housing delivery

Industrialized Construction (IC) implies application of industrial production methods originating from manufacturing to the traditional building construction system (Lennartsson and Björnfot 2012). IC methods that use off-site construction, prefabrication, and modularization (Lennartsson and Björnfot 2012) have been suggested as an approach to reducing process variation by *standardization* (Höök and Stehn 2008). In recent years, the building construction industry in the U.S. is beginning to use IC to overcome barriers of labor expertise, cost, quality, safety, and speed of construction. This is due in part to the lack of innovation in how we have attempted to improve the highly *standardized processes* entrenched in the U.S. construction marketplace. According to a recent McKinsey & Company report on productivity in the U.S. construction market, the U.S. construction industry productivity (measuring total output expressed in weight, length, or volume, and the input resource is usually in cost of labor or manhours) is lower today than it was in 1968 (McKinsey Global Institute 2017). They suggest a global effort is needed to modernize and upgrade the construction industry across the following board areas: (i) rethink design and engineering processes; (ii) improve procurement and supply-chain management; (iii) improve site-built execution; (iv) infuse digital technology, new materials and advanced manufacturing and automation; and (v) reskill the workforce.

The lack of productivity and innovation across the U.S. construction industry has also placed upward pressure on the construction costs of our building stock, resulting in increasing cost due to these inefficiencies in our construction processes. Since roughly 21 million, or one in six, households in the U.S. are apartments and condos (Samarripas, York and Ross 2017), *the initial focus of employing IC in the U.S. is for the production and delivery of affordable housing*. According to the Turner Center for Housing and Innovation, due to poor productively gains in the US construction industry, "the production of housing - especially infill multifamily housing – has become so costly to produce it demands rents or sale prices that are unaffordable for most people" (Galante, Draper-Zivetz and Stein 2017). In house building, and in the construction industry in general, IC methods consist mostly "offsite" technologies, moving work from the construction site to the factory (Pan, Gibb and Dainty 2007).

Review of permanent modular construction in the U.S.

According to the U.S. National Institute of Building Sciences' Off-Site Construction Council (OSCC), off-site construction is "the planning, design, fabrication and assembly of building elements at a location other than their final point of assembly onsite. As a subset of off-site construction, *modular construction* is a method to construct a building using three-dimensional or modular units, assembled and produced in a factory. Modular homes adopt a *permanent volumetric modular construction* approach and are built in accordance with the model building code adopted by each state for site-built (Steven Winter Associates, Inc. 2001).

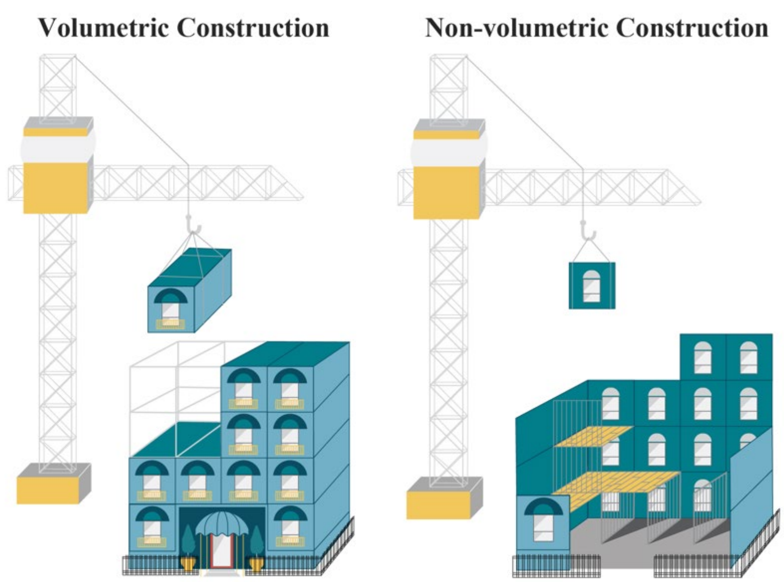

Figure 1: Volumetric modular construction where factory-built discrete units are being stacked on site (left) as opposed to non-volumetric panelized construction (right). *Source:* (BuildingGreen, Inc. 2018)

The 3D units are fully fitted out in a factory without exposure to weather before being transported to the site and stacked onto prepared foundations to form buildings (Musa, Yusof, et al. 2016), as shown in Figure 1. According to Modular Building Institute (MBI) in the U.S., "Modular construction is a process that constructs a building off site, under controlled plant conditions using the same materials and designed to the same codes and standards as conventionally built facilities but in about half the time." (Lu 2009). Modular construction involves 75 percent to 95 percent completion of modular apartment units in off-site factories (Smith and Rice 2015). More recently, the OSCC has identified the potential of modular construction for improving productivity and efficiency with a transition to further digitalization, innovative technologies, and new construction techniques. They regard it "as an important method for advancing the competitiveness and productivity of the domestic construction industry over the next 20 years." (National Institute of Building Sciences 2013). Recent studies report that modular construction can save up to 20% on hard costs and reduce construction time up to 50% (Stein 2016). Thus, many U.S. contractors see modular construction as an opportunity to remain competitive.

According to CoStar, in 2017, 45% of all new construction floor area in the U.S. was multifamily typology (U.S. Apartment Demand – A Forward Look 2017). As cities look to expand their affordable housing and apartment options, the demand for cost-effective permanent modular housing is growing. The Terner Center's report 'Building Affordability by Building Affordably' recognizes that modular construction facilitates rapid production of an affordably built supply of housing (Galante, Draper-Zivetz and Stein 2017). Since the apartment units can be constructed while the site and foundation are being prepared, instead of after, there are significant time and cost savings (Quale, et al. 2012). Modular builders may also economize on costs by reducing total lead time (the time it takes for one unit to make its way through the one-piece flow production line from start to end). To support the growing modular industry to deliver affordable multifamily buildings, many rural and industrial areas in U.S. are increasingly becoming manufacturing sites.[1] Overall, modular builders have successfully proven delivery of affordable multifamily buildings through faster construction timelines, improved productivity, and labor cost savings.

Integrating Energy Efficiency Strategies

Need to solve for energy burden

In addition to cost of construction, household energy costs are a key determinant of housing affordability. These costs continue to place a major 'energy burden' on tenants or homeowners. Compared to middle- and upper-income households that spend 5 percent or less of their total household income on energy purchases, low-income householders spend 10 percent or more of their income on energy expenses. The burden is even greater among the very poor, who are likely to spend an upwards of 20 percent on energy purchases (Hernández and Bird 2010). The U.S. Department of Energy`s (DOE`s) Office of Energy Efficiency and Renewable Energy (EERE) helped define the affordable housing issue in a much broader way to incorporate energy

[1] Leading such efforts are Factory_OS operating out of Vallejo, CA, Volumetric Building Companies in Hamlet, NC, Skender in Chicago's Southwest Side, and Blokable Inc. in Vancouver, WA. Furthermore, as a solution for homelessness in the U.S., design-build firm CannonDesign aims to employ an integrated design, manufacturing and assembly for upcoming multifamily project 'Los Angeles County + USC Medical Center Restorative Care Village'

burden challenges (Lee, Chin and Marden 1995). Their well-known report 'Affordable housing: Reducing the energy cost burden' highlights that despite being unburdened by rental or ownership, "affordable housing is often least energy-efficient" and prove detrimental to long-term affordability. Furthermore, for many of these households, high and volatile home energy prices jeopardize the use of home heating and cooling and increase the prospect of exposure to temperatures that are too hot in summer and too cold in winter (Snyder and Baker 2010).

While there may be unintended or secondary energy efficiency (EE) benefits to IC such as a tighter envelope due to higher construction quality in a controlled factory environment, the IC method of permanent modular construction has not been leveraged specifically to enhance EE. EE integration faces many challenges related to split incentives, highly first cost constrained, residential versus central metering, and feedback. For the wider building industry, there has been significant effort to optimize schedule impacts for modular construction (Arashpour, et al. 2016). *However, there has been minimal work to combine both the intrinsic benefits of IC methods with the installation of cost-effective EE strategies, advanced controls, distributed energy, and grid-friendly design strategies.* There is a need to prove that permanent modular construction can address housing affordability challenges for multifamily buildings by lowering cost of construction and energy burden.

From Zero-Energy Buildings to Zero-Energy *Modular* Buildings in the U.S.

A Net Zero-Energy building (ZEB) is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies (Torcellini, et al. 2006). In fact, a good ZEB definition should first encourage energy efficiency, and then use renewable energy sources available on site. The U.S. DOE Building Technologies Program has set a research goal of making commercial ZEBs marketable by 2025 (Torcellini and Crawley 2006).

A broad range of literature and strong expertise on EE and advanced controls integration to achieve ZEB exists for site-built projects.[2] Recent dialogue on ZEB in the U.S. has been shaped by a growing number of codes, standards and commitments.[3] However, it has been observed that building industry professionals who are interested in ZEB for their next project usually seek guidance in navigating through the process[4], especially for site-built multifamily buildings. In response to this, a broad range of pathways to achieve ZEB standards have been recommended by the DOE Zero Energy Ready Home (ZERH) program.[5] The 'Advanced Energy Design Guide (AEDG) - Achieving Zero Energy' series provides a cost-effective approach to achieve advanced levels of energy savings focused on site-built projects. AEDGs provide comprehensive design guidance, case studies and building energy modeling (BEM) by building type and climate zone (ASHRAE 2019). More importantly, AEDGs provide with a broad range of pathways to design and build commercial ZEBs (Advanced Energy Design Guide for K-12 School Buildings: Achieving Zero Energy 2018, 62). Based on review of such existing literature on site-built ZEBs, Table 1 below enlists summary of strategies and their components.

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[2] Mixed-use and multifamily projects completed in 2019 such as Boulder Commons, UC Davis Student Housing and Revive Properties in Fort Collins, CO are exemplary site-built ZEB projects.
[3] Recent ZEB trends include ZERO CODE, LEED Zero and '100 percent Renewable Commitments' driving ZEB codes across the country.
[4] Non-profit organizations in the U.S. such as Zero Energy Project provide ZEB guidance to builders.
[5] DOE is also coming up with a ZERH Multifamily Program for site-built multifamily projects.

Table 1. Summary of strategies and components for site-built to achieve ZEBs

Site-built strategies	Components
Building and site	Building design, site design, and building orientation strategies
	Planning for renewable energy
	Use of open source Building Energy Modeling (BEM) Platform
Building envelope strategies	Envelope construction strategies and factors
	Compartmentalization/Air-tight Envelope
	Thermal mass, well-insulated envelope and thermal bridging
Daylighting	Design and space specific strategies
	Solar Heat Gain Coefficient (SHGC) multipliers for projections
Electric lighting	Luminaire recommendations, design and space specific strategies
	Advanced Control strategies
Plug load	Plug load management
	Power distribution systems
Kitchen equipment	Equipment, design strategies and performance specifications
	Heat recovery
Service water heating (SWH)	System types and design Strategies
	Electric resistance and Heat pump water heater recommendations
Mechanical equipment solutions	Design strategies and equipment recommendations
	Chilled/hot-water system with single-zone AHU
	Air-source variable-refrigerant-flow (VRF) multi-split heat pump
	Ground source heat pump (GSHP)
	Dedicated outdoor air system
Renewables and storage systems	PV ready design and implementation strategies
	Energy storage system
	Building-Integrated PV and building-attached PV
	Electric vehicle integration

As an emerging affordable housing solution, Vermont Energy Investment Corporation (VEIC) assessed market readiness for 'Zero-Energy Modular' (ZEM) buildings and trends across many states in the U.S. A trend in affordable ZEM buildings has been seen for residential, mainly in accessory dwelling units (ADUs) and single-family detached homes.[6] According to a recent VEIC report, ZEM combine the benefits of no to low energy costs with the efficiencies of modular construction. All-electric and highly efficient, ZEM homes are often outfitted with rooftop solar arrays and use about as much energy as they produce each year. However, affordable ZEM buildings are not being designed, constructed and delivered across the U.S. at the rate one would expect as highlighted by VEIC's market analyses for Vermont, Delaware, Massachusetts, New York, Colorado, and Oregon. According to VEIC's analyses, the limited capacity for building ZEM homes is currently the most significant barrier to advancing the ZEM housing option nationally (Juillerat and Donovan 2019). Additionally, there has been limited investigation on trade-offs between site-built and off-site construction from the perspective of energy savings and environmental impact.[7]

[6] An increasing number of ZEM homes in the U.S. created by permanent modular builders such as Gaia Homes, Module, Living Homes, and Dvele that incorporate ENERGY STAR products and Indoor airPLUS label
[7] According to McGraw-Hill Construction's study 'Increasing Productivity in the Construction Industry', 76% of modular builders report that IC decreases the amount of construction waste, with 41% reporting decreases of 5% or more. Not only are these gains environmentally beneficial, but they also are financially beneficial, with less waste translating to cost savings and higher return of investment

Methods

Industrialized Construction Assessment Framework

A major barrier to increased production of ZEM multifamily buildings is the lack of technical know-how to effectively map and implement the best practices of ZEB from site-built to off-site without undermining IC benefits such as lower cost of construction and reduced lead time. As affordable housing delivery in the U.S. by permanent modular construction continues to grow, there is a need to perform detailed study on proven successes in ZEM multifamily buildings, opportunities of improvement, and current limitations.[8] Considering the constant changes and evolution witnessed in the industry, research and open source knowledge dissemination is important to learn from and improve best practices by engaging with the relevant stakeholders.

NREL's ICI Team[9] aims to claim this missed opportunity by addressing the primary research question: "*How can optimal integration of EE strategies and advanced controls with IC be achieved with little or no additional cost, labor, and lead time*?"

An assessment framework provides a structured map of the stages, methods and outcomes of a given study that engages stakeholders through a novel workflow and achieve the desired output. The proposed 'Industrialized Construction (IC) Assessment Framework', as shown in Figure 2, delineates an integrated workflow that aims to guide permanent modular builders to: i) identify site-built EE strategies that would be easy to manufacture and assemble at their IC factories with lowest possible additional cost, labor, and lead time, ii) design with the chosen set of strategies to achieve a standardized product by creating a Building Information Model (BIM) of the modular building, iii) quantify and iterate upon process-optimization, cost-optimization, and energy-optimization benefits through a digital twin of the standardized process and product, and iv) effectively utilize the desired output of Factory Information Model (FIM) as a virtual three-dimensional representation of how the integrated EE strategies and automated controls render the apartment units as ZEM or ZERH and makes their IC methods more efficient.

Design for Manufacturing and Assembly Selection Criteria

The initial goal of the assessment framework is help arrive at a set of minimum viable strategies that qualify for off-site integration. The selection criteria of Design for Manufacturing and Assembly (DfMA) is introduced to identify site-built EE strategies that could be *easily manufactured and assembled* at a typical IC factory. According to the seminal book 'Design for Manufacturing and Assembly: Concepts, Architectures and Implementation,' the operating principle of chunking or clustering helps the designer in Design for Manufacturing (DfM) to integrate the manufacturing criteria while enables Design for Assembly (DfA) in order to ease the assembly process (Molloy, Warman and Tilley 2012). Similarly, the criteria that inform qualification under this assessment framework include *lowest possible additional cost, labor, and lead time*.

[8] For affordable ZEM multifamily buildings, Solar Home Factory who has developed factory-built solar powered core that includes integrated rooftop solar and integrated EE strategies.

[9] NREL's Industrialized Construction Innovation (ICI) Team investigates the opportunities to leverage modular construction in a factory as the prevalent IC method to deliver affordable zero energy modular housing.

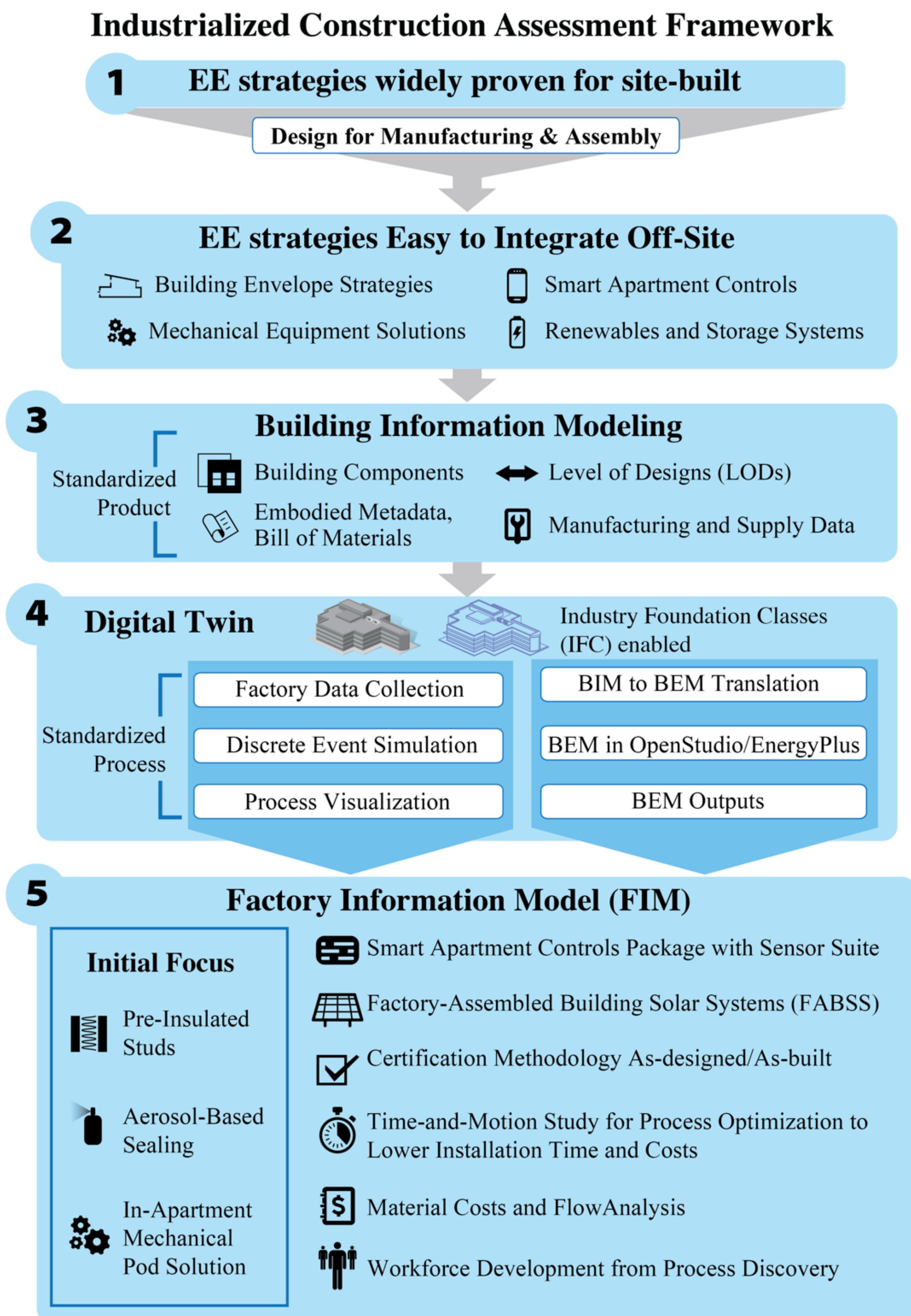

Figure 2: The proposed 'Industrialized Construction Assessment Framework' delineates the five recommended stages of the integrated workflow, easy-to-comprehend for permanent modular builders.

The four strategies that DfMA-based selection criteria help identify and qualify from Table 1 to be integrated off-site are: i) Building Envelope Strategies, ii) Mechanical Equipment Solutions, iii) Smart Apartment Controls, and iv) Renewables and Storage Systems. EE strategies from Table 1 that cannot be easily manufactured and assembled into the apartment units at a typical IC factory would be generally disqualified by permanent modular builders (and by the assessment framework). For example, continuous insulation on external wall, centralized solution of air-source variable-refrigerant-flow (VRF), and ground source heat pump add to on-site work and undermine IC benefits by increasing costs, labor, and lead time.

Table 2. Summary of strategies for off-site to achieve ZEM multifamily buildings

Off-site strategies	Components
Building envelope strategies	Insulation systems maximized for life cycle cost savings
	Aerosol-based Sealing Technology for air-tightness improvements
	Pre-Insulated thermally broken studs (such as TStuds[10])
	Advanced Wall Framing technologies (Pre-Framer Machine)
	Building Envelope Compartmentalization
Mechanical equipment solutions	Integrated Mechanical system pod solution for space conditioning and water heating (in-unit HVAC and heat pump water heater)
	Heat recovery options from wastewater
	Integrated exhaust and ventilation heat recovery with dehumidification/heating/cooling solutions
	Ventless dryers to eliminate exhaust vent maintenance
	Grid controllable All-electric domestic water heater
	Induction cooking
Smart apartment controls	Occupant Engagement Platform
	Advanced Controls Integration
	Enable single utility meter with software submetering
	Grid-integrated HVAC and hot water controls, utility price signaling
	GEB controls, sub-metered module with hourly real-time pricing
Renewables and storage systems	Single meter to enable large-scale PV, with unit submetering
	Modular electrical rooms with battery UPS & demand management
	In-unit battery storage for demand management and backup UPS
	Factory-Assembled Building Solar Systems (FABSS)

Selected EE strategies and their respective components, as shown in Table 2, qualify because they could be seamlessly integrated with little or no additional cost, labor, and lead time. For example, instead of framing walls in the factory using standard studs followed by on-site continuous insulation, pre-insulated thermally broken wall-framing studs could be used as a consolidated off-site process of advanced wall framing. Th*e 'down select' criteria from the non-exhaustive list in Table 1 to arrive at the four strategies in Table 2 has been heavily dependent on anecdotal feedback from wood-framed and steel-framed US modular builders who prefer moving as many laborious activities as possible from the construction site to the construction factory. Scheduling construction and assembly such that more and more work is delegated to the modular factory implies monetary savings. Such a seemingly basic shift in location of the construction process leads to great reduction in complexity, first cost, lead time, waste, and greater opportunities for innovative compartmentalization and integration of energy efficiency strategies to each modular unit.* For example, instead of centralized solution of VRF mechanical

[10] Benefits of lower framing costs, labor, lead time, and material use from TStuds

system for multifamily buildings, permanent modular builders can choose a decentralized solution of integrated mechanical system pod solution in each modular apartment unit. A precedent off-site prototyping project in the UK for similar 'utility cupboards' has proven DfMA-based selection criteria to be effective in lower cost of production by 44% and reduced lead time by 42%.[11]

The components enlisted in Table 2 would need to be part of the final building design. Increased adoption of these strategies by permanent modular builders as part of their business-as-usual clearly has major benefits. However, there is a need to quantify these benefits through modeling and simulation prior to initiating pilots at the IC factory in order to de-risk the integration effort. Permanent modular builders also express the need to use relevant modeling and quantification approaches to evolve their decision-making tools. A back-end research and development aspect and a front-end interface aspect of the assessment framework can begin to address these needs.

BIM-based Digital Twin for Process Modeling and Energy Modeling

Building Information Modeling (BIM) is the process of creating an accurate, intelligent and computable three-dimensional (3D) virtual model of a building (Olofsson, Lee and Eastman 2008). It has been extensively used during the past two decades for product family design to optimize design, minimize production waste, manage supply chain, standardize components of products, and manage product changes and options (Jian, et al. 2014). This makes BIM an ideal tool to be used by permanent modular builders in order to achieve a standardized product. BIM has proven to enable value stream mapping (VSM) of the IC factory and generate manufacturing schedule and supply data at different stages of IC (Moghdam, Alwisy and Al-Hussein 2012). Thus, the proposed IC Assessment Framework encourages permanent modular builders to leverage BIM for creating, storing, and sharing information for their standardized products and processes on: i) Building Components, ii) Level of Designs (LODs), iii) Embodied Metadata and Bill of Materials, and iv) Manufacturing and Supply Data. When designing with the selected four strategies, the 3D BIM model of the modular multifamily building would store its related information. For example, within BIM environment, the walls of each apartment unit could be designed directly using pre-insulated thermally broken stud components, and each apartment could be designed and simulated with in-unit integrated mechanical system pod solution/

Though 3D BIM models consolidate all necessary design-build information within its geometries, they inherently have two limitations (of particular interest to permanent modular builders) as follows: i) lack of process information to enable optimization of permanent modular construction of the final built product and ii) lack of energy information to enable optimization of energy performance of the final built product. Since all Architectural Engineering and Construction (AEC) data of the modular building within BIM are Industry Foundation Classes (IFC)- compatible,[12] the two identified limitations in 3D BIM model can be filled by creating a digital twin. The digital twin represents both the IC process and the final built product. The process-based digital twin, unlike other kinds of digital twins, is defined as a virtual representation of a modular construction factory that integrates information regarding its

[11] Utility Cupboards from Modern Flying Factories in the UK
[12] IFC facilitates the sharing and exchange of information among IFC-compatible software applications such as ability to import BIM directly to Unity Technologies' real-time 3D engine and ability to import BIM to open source Building Energy Modeling platform (OpenStudio and EnergyPlus) through BIMServer.

physical layout, interaction between multiple heterogeneous resources, and underlying process maps. The digital twin could also be defined as a dynamic virtual model of the factory that is more than the sum of its individual components including static 3D CAD models of the factory floor and equipment, and non-visual schematics of process flows. As shown in Figure 3, the 3D BIM model and IFC-enabled digital twin forms the back-end development aspect of the assessment performed by process and energy optimization experts.

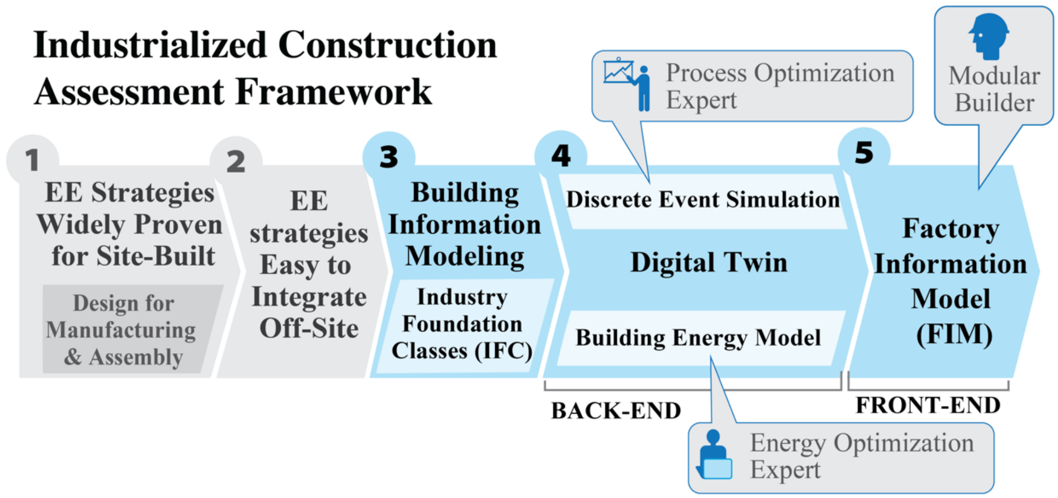

Figure 3: Back-End and Front-End of Industrialized Construction Assessment Framework. Back-end represents the research and development aspect with stage 3 (Building Information Modeling) and stage 4 (Digital Twin) - i) Discrete Even Simulation (DES): Process optimization involves sensor-based data collection from the IC factory and time-and-motion analyses using DES models[13] to visualize an end-to-end permanent modular construction process on Unity3D; ii) Building Energy Modeling (BEM): Energy optimization using open source BEM platform such as OpenStudio/EnergyPlus for design flexibility and to quantify trade-offs between the envelope insulation, HVAC systems, and loads across the year.[14] Front-end represents the interface aspect with stage 5 (FIM) enabling direct user-friendly interaction from builders.

The digital twin enables constant iteration upon process model and energy model results in order to reach a set of desired outputs such as accurate quantification of trade-offs that could be beneficial to permanent modular builders. Under stage 4, Discrete Event Simulation (DES) model would determine the process implications of adding a new component to the existing process by enabling forecasting of operational metrics. Developed by process optimization experts, DES uses machine learning algorithms for process discovery and virtually simulating integration of the four strategies with lowest possible costs, labor, and lead time.

As shown in Figure 3, parallel to DES, Building Energy Modeling (BEM) would quantify energy savings by applying EE strategies designed into the 3D BIM model for specific climatic conditions. Such an interoperable workflow opens up opportunities to develop novel value

[13] DES is a proven method for modeling operations that involve uncertainty in durations, include require complex activity startup conditions, and involve interdependence of resources in the operation. The *jStrobe* DES engine developed by Dr. Joseph Louis (OSU) will be used to model and analyze operations involved in IC methods.
[14] BEM allows for the sizing of systems to methods other than the traditional 0.4% design condition and worse case scenarios. BEM would be used to meet performance-based energy code compliance in place of prescriptive construction compliance (e.g. R-21 wall), such as a relatively intensive space heating could be traded for efficiency gains in lighting and cooling for California's modular builders (See ASHRAE 90.1 Appendix G or T-24 sec 140.1).

streams for energy modeling. Traditionally, cost estimates in energy modeling include determining construction costs, determining project costs, and comparing the current simulation to a reference case for marginal increases. We know that the output of DES provides with these first costs and also contextualizes the cost values based on the modular construction process in the factory, instead of site-built average values from literature. This output can now serve as an input to EnergyPlus (engine of BEM environments such as Autodesk System Analysis, BeOpt and OpenStudio) thereby enabling more robust least-cost curve analyses for the whole lifecycle of the modular building. While the modular builder might be primarily interested in first cost outputs from DES, stakeholders such as developers and building owners would benefit from taking informed lifecycle decisions for their modular buildings based on the most cost-effective combination of energy efficiency and renewable-energy option. BEM would also inform the requirements of permanent modular construction to correspond to the site's energy codes and strategies (for example, above-code levels of insulation for an electric heating system where whole building electrification is required).

NREL's ICI Team has partnered with Volumetric Building Companies (VBC), a high-performing permanent modular builder with IC factory in Hamlet, NC. VBC has expertise in wood-framed modular construction to deliver affordable multifamily buildings in their region. The plan is to utilize the assessment framework and digital twin for research and analysis of all the components under the selected four strategies in Table 2. The preliminary results from comparative analysis of discrete stations at VBC's IC factory for two building envelope EE strategies of advanced wall framing and aerosol-based sealing (as shown in Figure 4 and 5) demonstrate a range of potential process optimization and energy saving benefits. In this way, both Discrete Event Simulation and Building Energy Modeling can help i) compare scenarios related to on-site and off-site integration for all four strategies and ii) compare scenarios related to multiple iterative pathways during off site integration for each strategy.

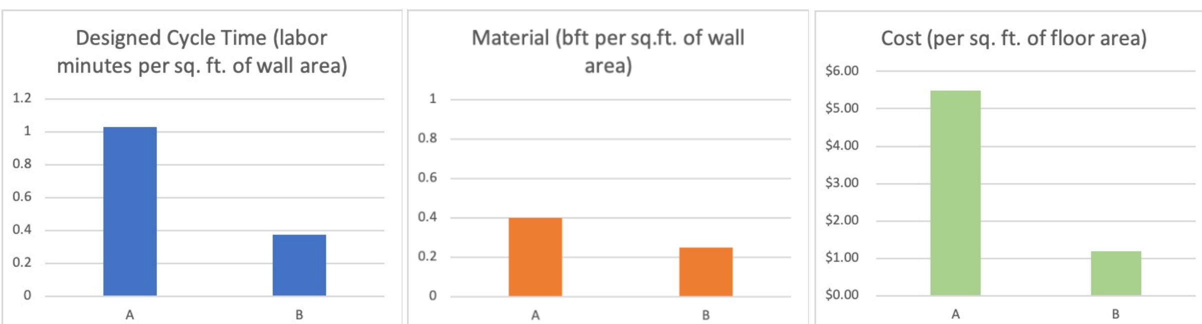

Figure 4: Comparative Analysis from digital twin for Building Envelope EE strategy of Advanced Wall Framing on designed cycle time, material, and cost. According to the analysis, (A) wall framing with pre-insulated thermally broken studs in IC factory reduces the designed cycle time by 63%, total material used by 38%, and cost (for material and labor) by 78% in comparison to (B) wall framing with standard studs followed by on site continuous insulation.[15]

In addition to quantifying significant reduction in designed cycle time (a subset of lead time and refers to the time it takes for a workstation to produce a product when there are little or no interruptions), material use, and costs (as shown in Figure 5), the digital twin of advanced

[15] Key assumptions are floor area = 750 sq. ft., long wall area = 886 sq. ft., continuous insulation cost = $4 / sq ft, continuous insulation labor time = 0.6 labor minute per sq. ft.

wall framing has enabled study of the effects of integration into the rest of the production line. The digital twin's DES model compares the base-line plan of work against which actual work can be compared to for deviations in performance. This can enable builders to identify bottlenecks in the process before they arise and thus optimize the configuration of the IC factory layout and resource allocation to accommodate the changes in the process. Additionally, the digital twin for advanced wall framing proves that productivity savings from IC methods also apply to energy analysis for every apartment unit through its energy model. Similarly, in addition to results in Figure 5, the digital twin of aerosol-based sealing would help identify the best timeframe for an aerosol-based sealing station to plug-in, perform its operation and render that apartment unit with better airtightness.

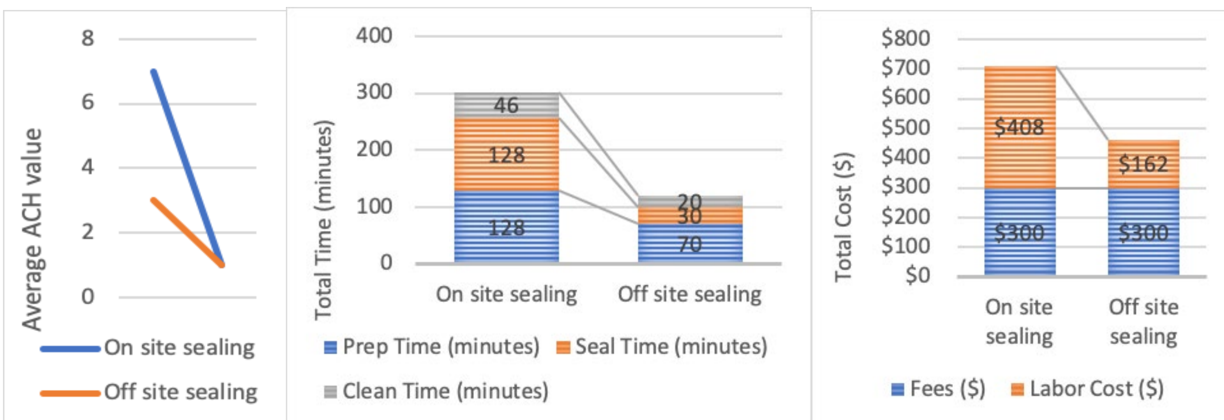

Figure 5: Comparative Analysis from digital twin for Building Envelope EE strategy of Aerosol-based Sealing on starting airtightness (in ACH50), designed cycle time, and cost. According to the analysis, aerosol-based sealing in IC factory of factory-built modular apartment units (off site sealing) starts in modules that are 60% more airtight due to IC methods and takes 60% less time to complete the three stages of preparation, sealing, and cleaning in comparison to aerosol-based sealing in on site in site-built apartment units (off site sealing). Due to faster significantly faster sealing time, off site sealing brings down costs by 40%.[16]

This could either be during an idle time or parallel to a non-intrusive process. Additionally, the digital twin's energy model affords IC the best cost value for EE strategy of aerosol-based sealing and the flexibility to comply with energy standards by modeling performance rather than the prescriptive values for building envelope systems. The digital twin, at different levels and scales, can answer different questions regarding process and energy. Other integration efforts under development with VBC's IC factory include an integrated mechanical system pod solution that would serve purposes of space conditioning and water heating for each apartment unit. This pod solution is being designed through DfMA chunking or clustering process in BIM and its thermal cycles and energy performance is being optimized using OpenStudio/EnergyPlus. The next steps include performing similar standalone analysis for other EE strategies, connecting different discrete stations and their results for the whole IC factory, performing cohesive analysis of process and energy optimization displayed as a Factory Information Model, demonstrating pilots, and documenting lessons learnt.

[16] Key assumptions are average floor area of apartments = 400 sq. ft, average enclosing volume = 3500 cu. ft., number of workers = 3, labor charge of 3 workers = $27 per hour, Aerobarrier fees = $300.

Factory Information Model

The IC Assessment Framework presents its final analytics to the permanent modular builders as a front-end interaction aspect called 'Factory Information Model' (FIM), as shown in Figure 3. The back-end digital twin would be visualized in real-time as a fly-through virtual representation of the modular builder's IC factory (as shown in Figure 6), enabling direct interaction with a wide range of assessments, results and metrics. This would inform decisions by the builder and ensure increased adoption and off-site integration of EE strategies and advanced controls. Once a baseline FIM has been created for a particular factory with input from its factory managers and stakeholders, the user can readily inspect the performance of the factory under an endless number of hypothetical scenarios by changing any aspect of the factory and assembly line. Examples of such changes include varying the number of workers assigned to a station, varying the number of surge spaces for different stations, alternating the placement of various tool stations, etc. Because of the tight integration between the digital factory layout, the resources, and the process, the result of any of these changes will be considered in the final performance metric provided by the factory.

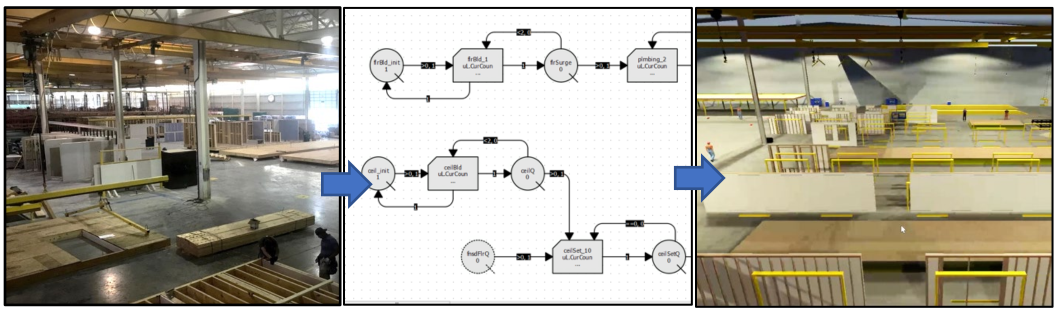

Figure 6. FIM of VBC's IC factory under development. A variety of sensors deployed to measure the baseline performance of VBC's IC factory (left) which serves as input to DES model's discrete stations (middle) of the digital twin. FIM of the entire VBC's IC factory displaying results (right).

More precisely, the project output involves elemental building blocks in the form of a 'library' of 3D components to enable any modular factory builder to create a FIM for their own modular construction factory through an intuitive drag-and-drop interface. The library includes elemental steps that are performed by workers and equipment as well as a list of 3D stations such stations include floor build, rough electrical and plumbing, and dry wall stations. The library would also store 3D models of several innovative components, advanced building construction[17] methods, and technologies of strategies *such as higher airtightness of building envelope from aerosol-based sealing, advanced wall framing with pre-insulated studs, compartmentalization, advanced controls, in-apartment mechanical pod solution, and factory-assembled solar PV*.

Conclusion

Lessons learned from ongoing work with VBC and other permanent modular builders can be broadly applied to other IC factories and their respective methods. The potential impact from IC Assessment Framework scales beyond the ongoing projects by translating to other builders in

[17] The work falls under Advanced Building Construction with Energy-Efficient Technologies & Practices (ABC) initiative by US DOE that aims to develop new construction technologies enabling energy-efficient buildings.

the modular building industry. The advantages in using advanced analytical tools such as 3D BIM, DES, and BEM within the framework would be prototyped by working closely with high-performing permanent modular builders and then disseminating for wider adoption throughout the building construction industry at large. By proving the IC benefits to enhance EE, the ongoing projects has the potential to elevate the US modular industry at the cutting-edge of the entire building industry. Such an effort could potentially deem the niche industry to be celebrated as torchbearers of 'affordability through innovation' and industry leaders accelerating a Clean Energy Future for our built environment.

Demonstrating best practices using Factory Information Model for optimal contexts can stimulate the building industry to analytically assess and accurately leverage IC benefits by delivering affordable housing at scale, to lower energy burden of tenants and homeowners by enhancing EE, to invest in U.S. construction workforce by improving productivity, and to meet the industry-wide goals of net-zero energy and energy efficiency by integrating DfMA-qualified strategies. Successful adoption of the IC Assessment Framework in ongoing projects act as initial steps towards establishing thought leadership on Industrialized Construction (IC) of Zero-Energy Modular (ZEM) multifamily buildings, both nationally and globally. IC of ZEM multifamily buildings commence the development of a transformational pathway for our Clean Energy Future, aiming to address affordable housing crisis by lowering construction costs as well as solve for energy burden by lowering household energy bills.

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